Review of Gravitational Wave Results from the LIGO-Virgo-Kagra Collaboration

Portorož 2021: Physics of the Flavourful Universe, 21 - 24 Sep 2021

VIR-0958A-21

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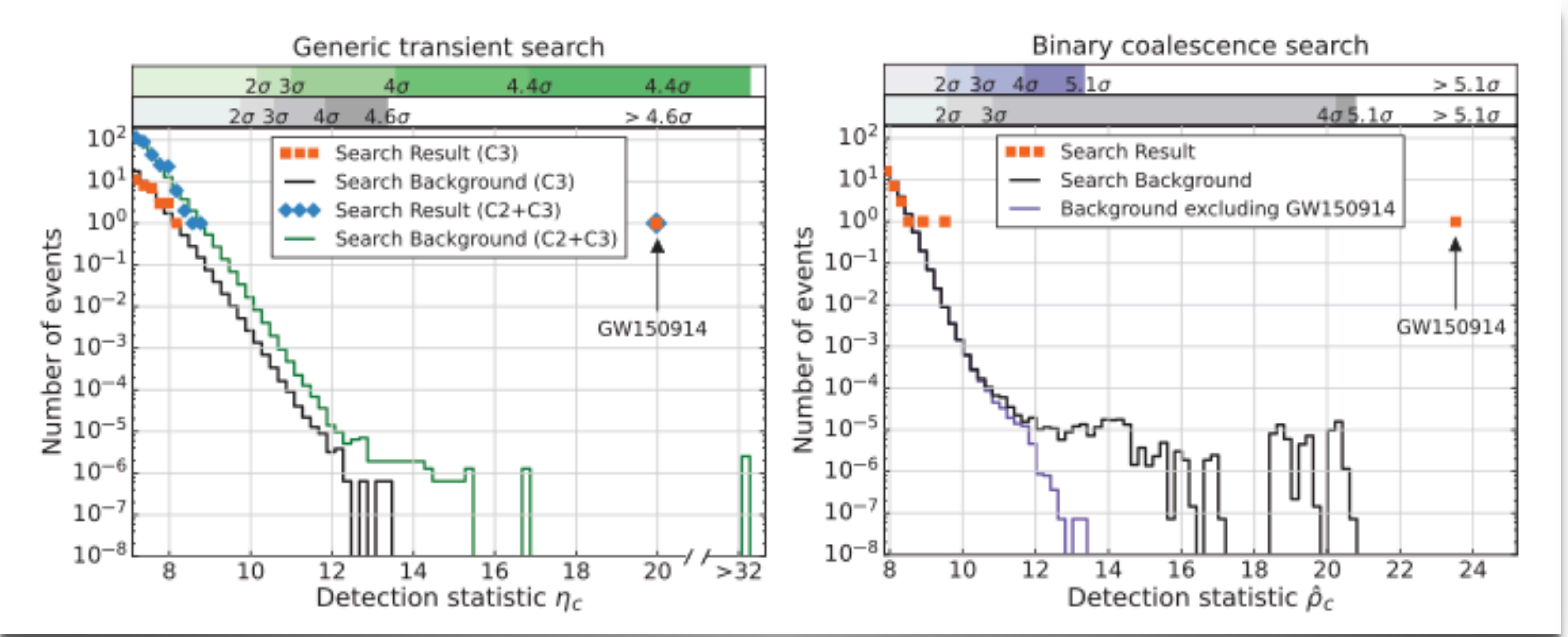
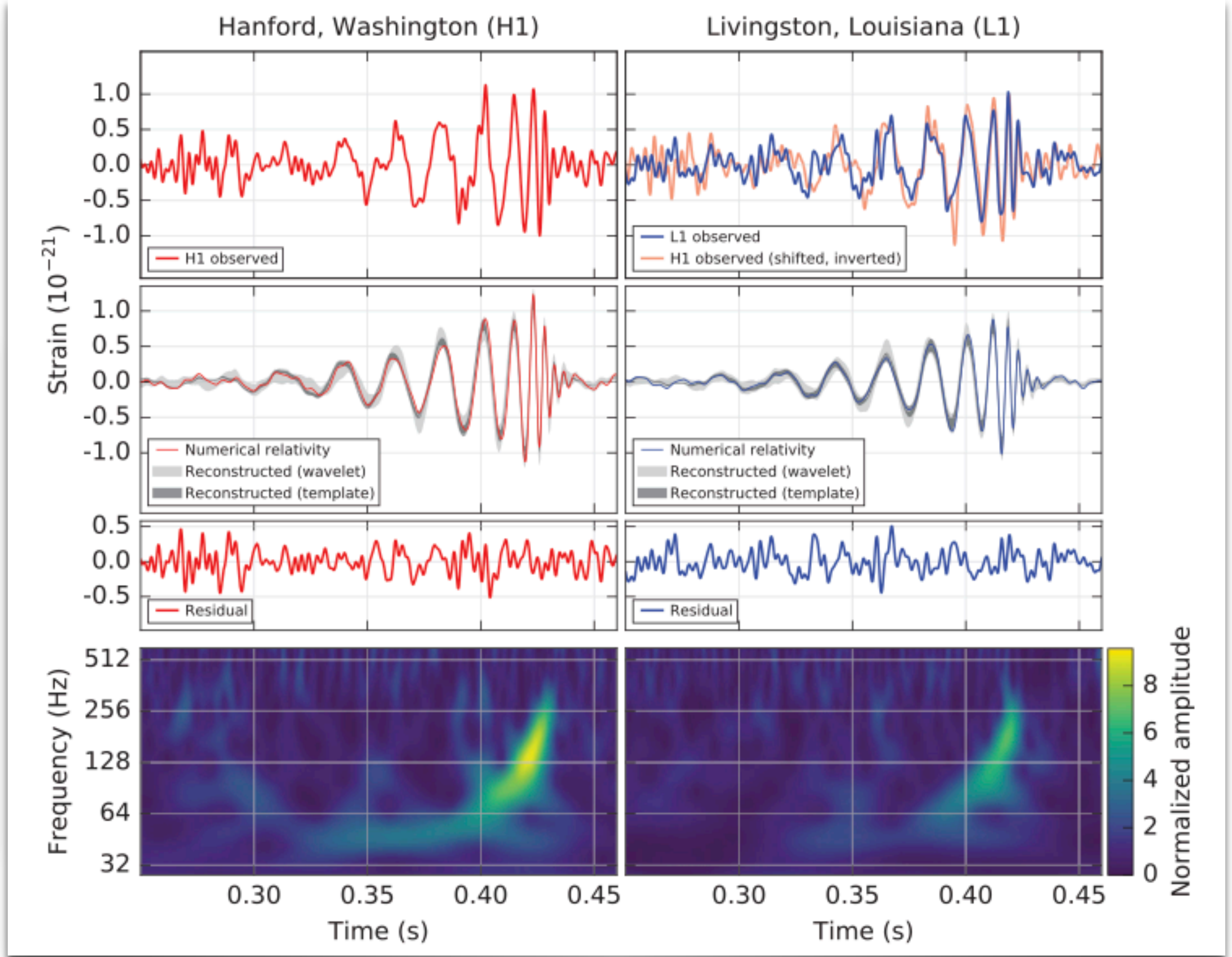
OUTLINE

- Birthday of GW150914
- Current detector status
- GW catalogue so far
- Particular events:
    - Asymmetric BBHs
    - Another BNS
    - Intermediate mass BH
    - NSBH discoveries
- Search efforts for other types
- The future

THE BIRTH(DAY) OF GW ASTRONOMY (14-SEP-2015)

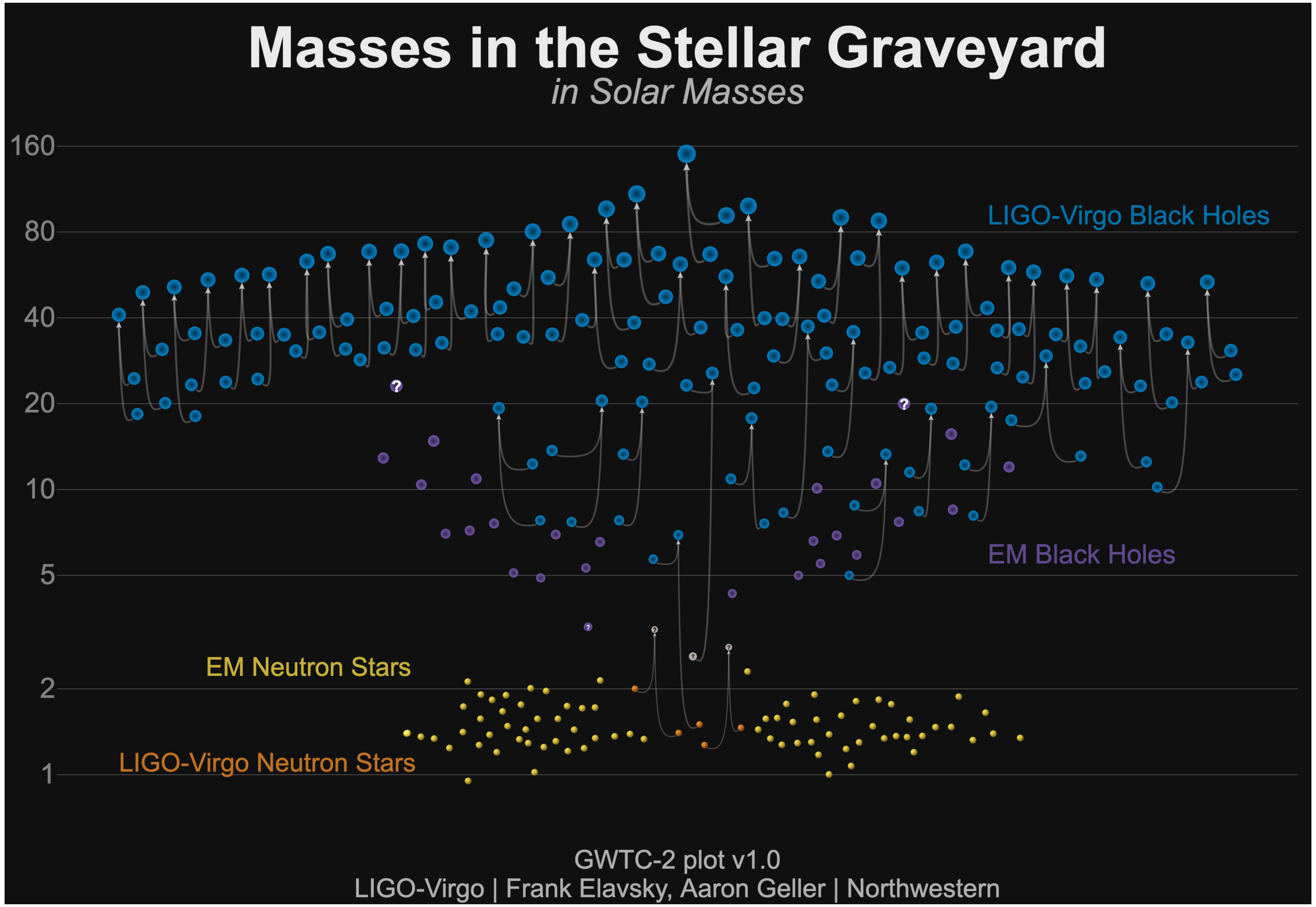
https://en.wikipedia.org/wiki/Happy_Birthday_to_You#/media/File:Birthday_candles.jpg



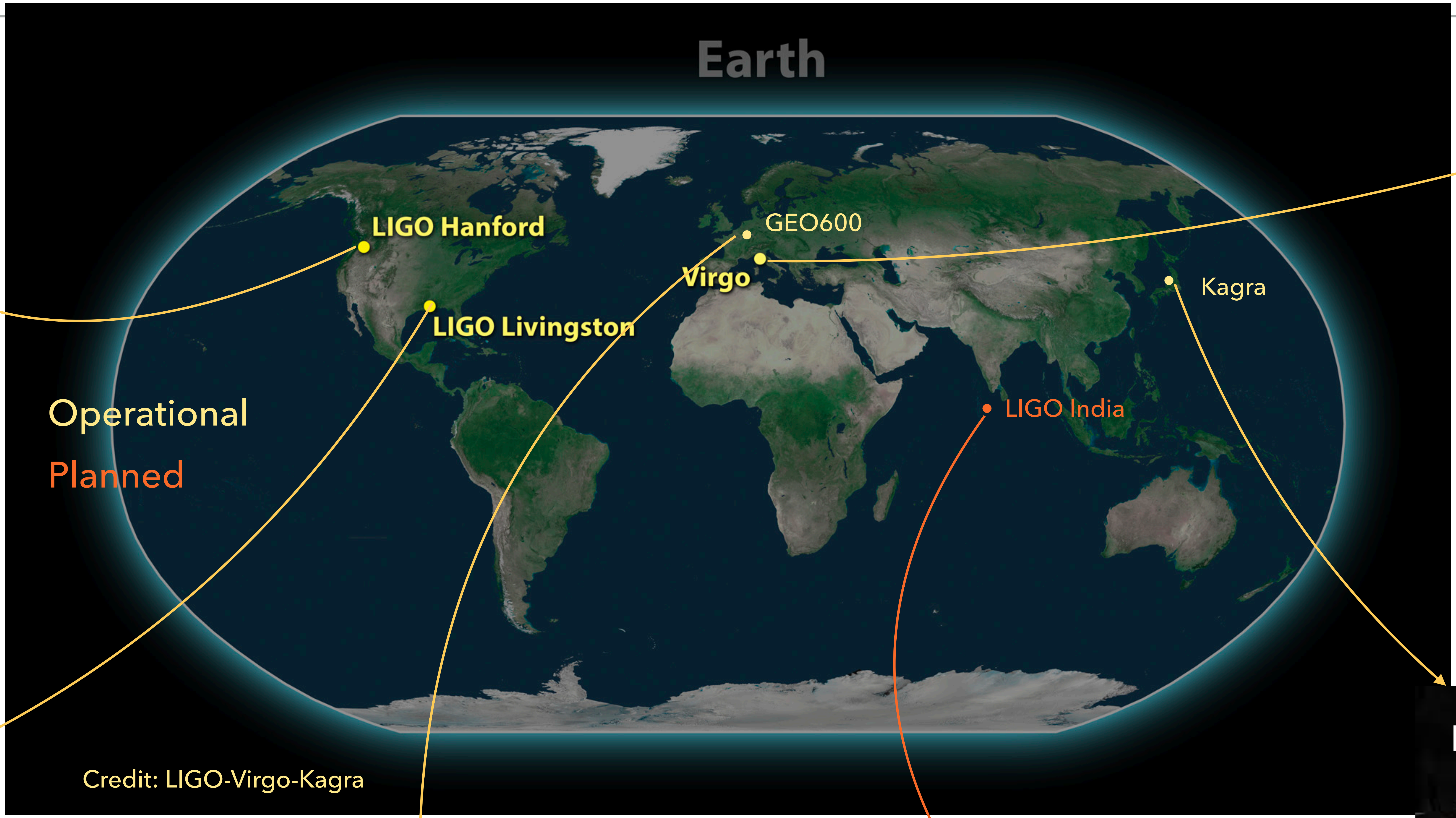


https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.116.061102

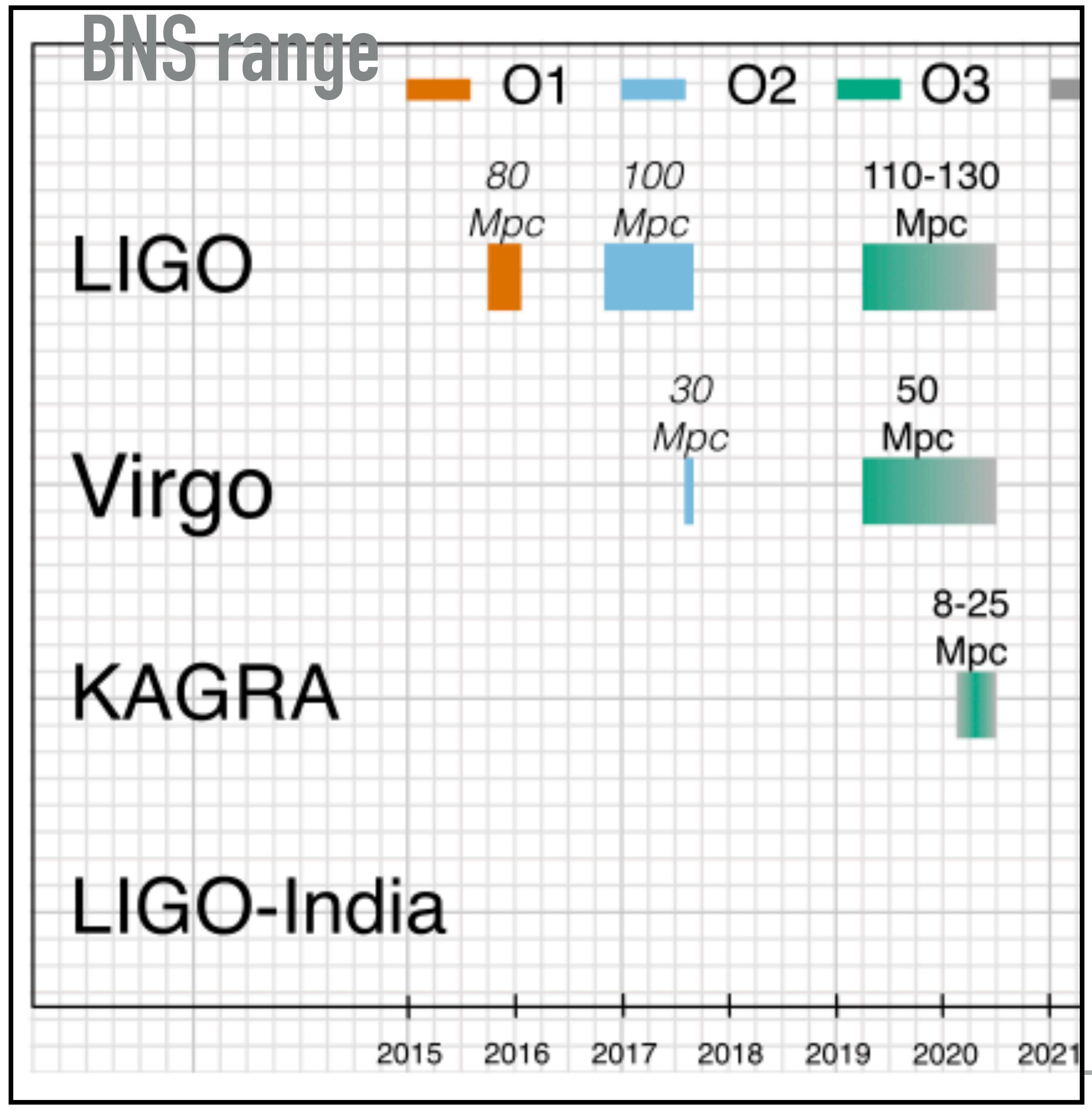
GW SIGNALS SO FAR …

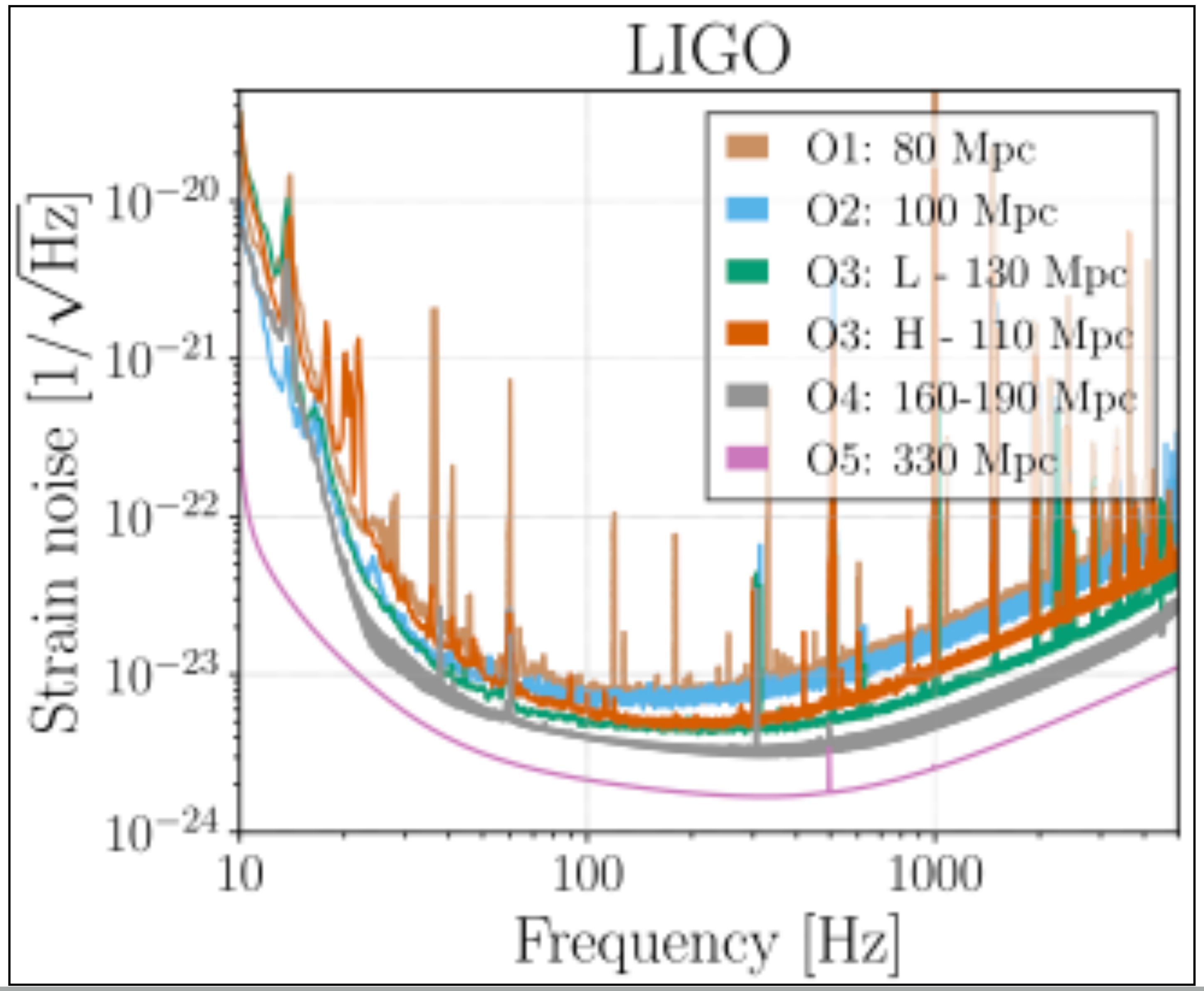


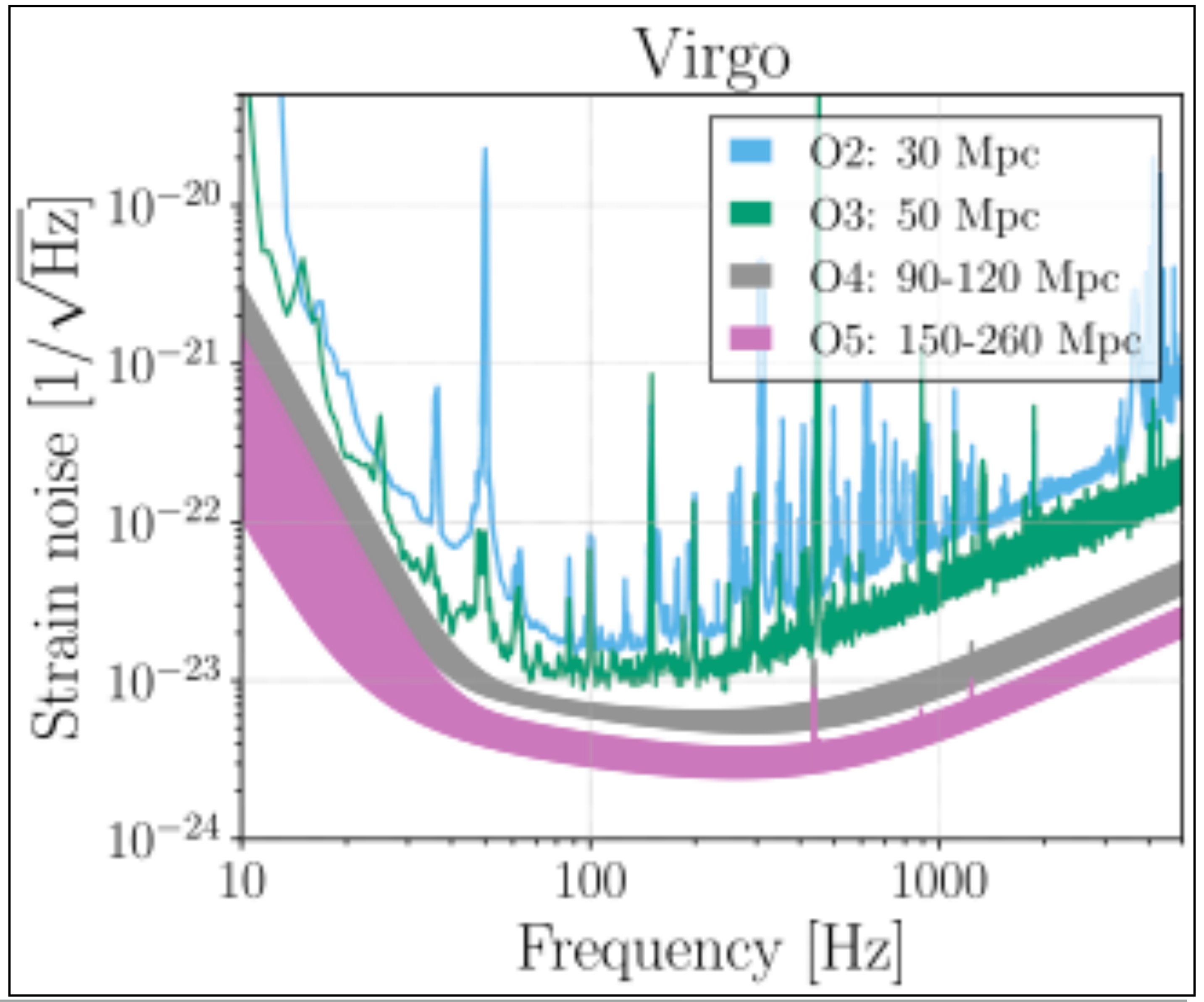
CURRENT DETECTORS



O1	UPGRADE: NO DATA	O2	UPGRADE: NO DATA	O3a	O3b
Sep'15 – Jan'16		Nov'16 – Aug'17		Apr'19 – Mar'20	



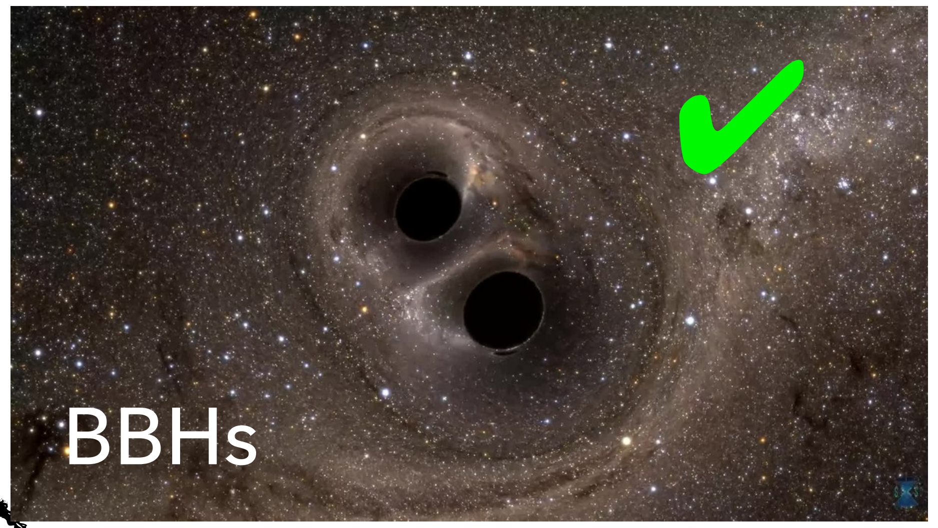


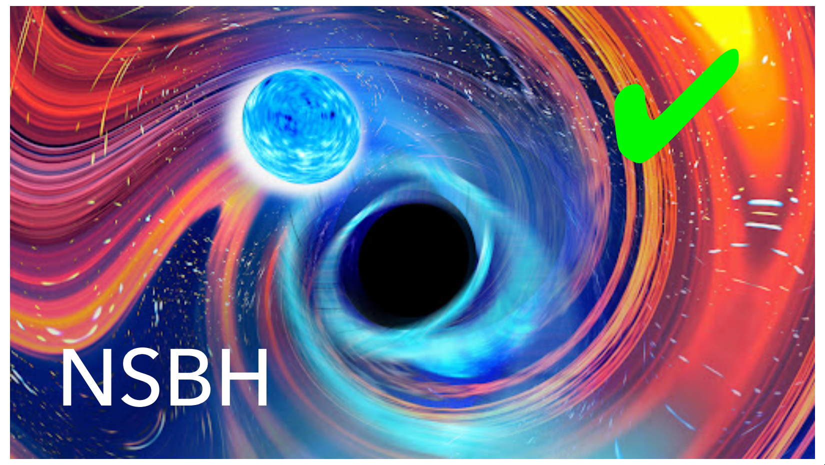


Abbott et al. 2020. LRR 23:3

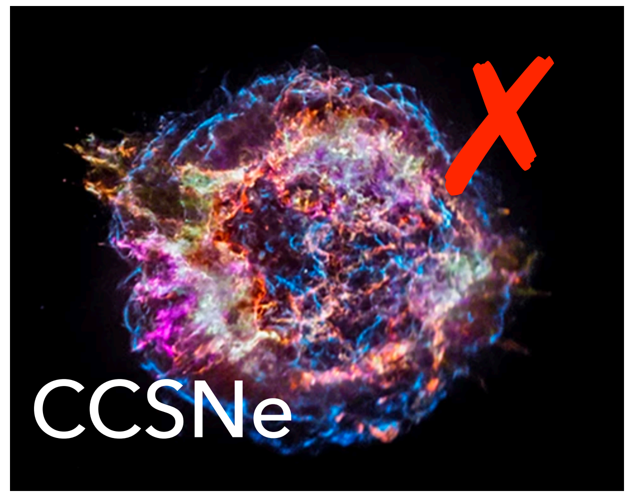
TYPES OF DETECTED SIGNALS (SO FAR ...)

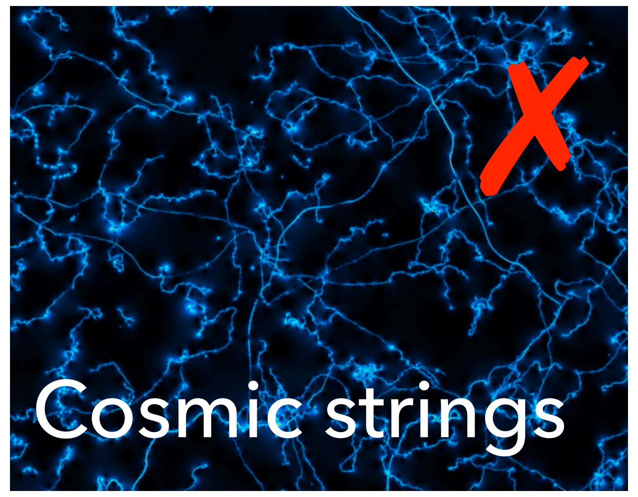
Binaries of compact objects



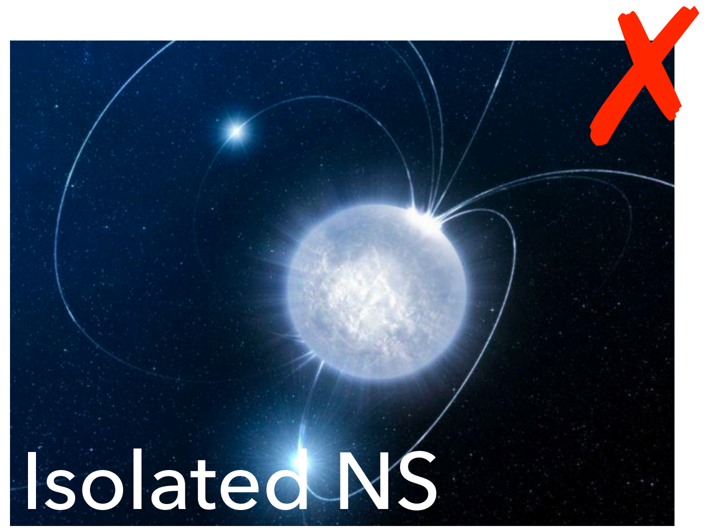


Transient unmodelled signals

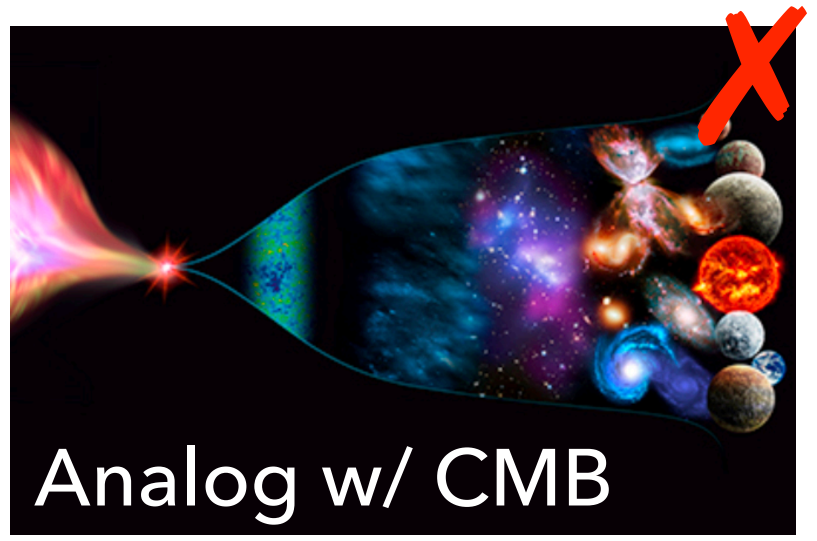




Continuous signals

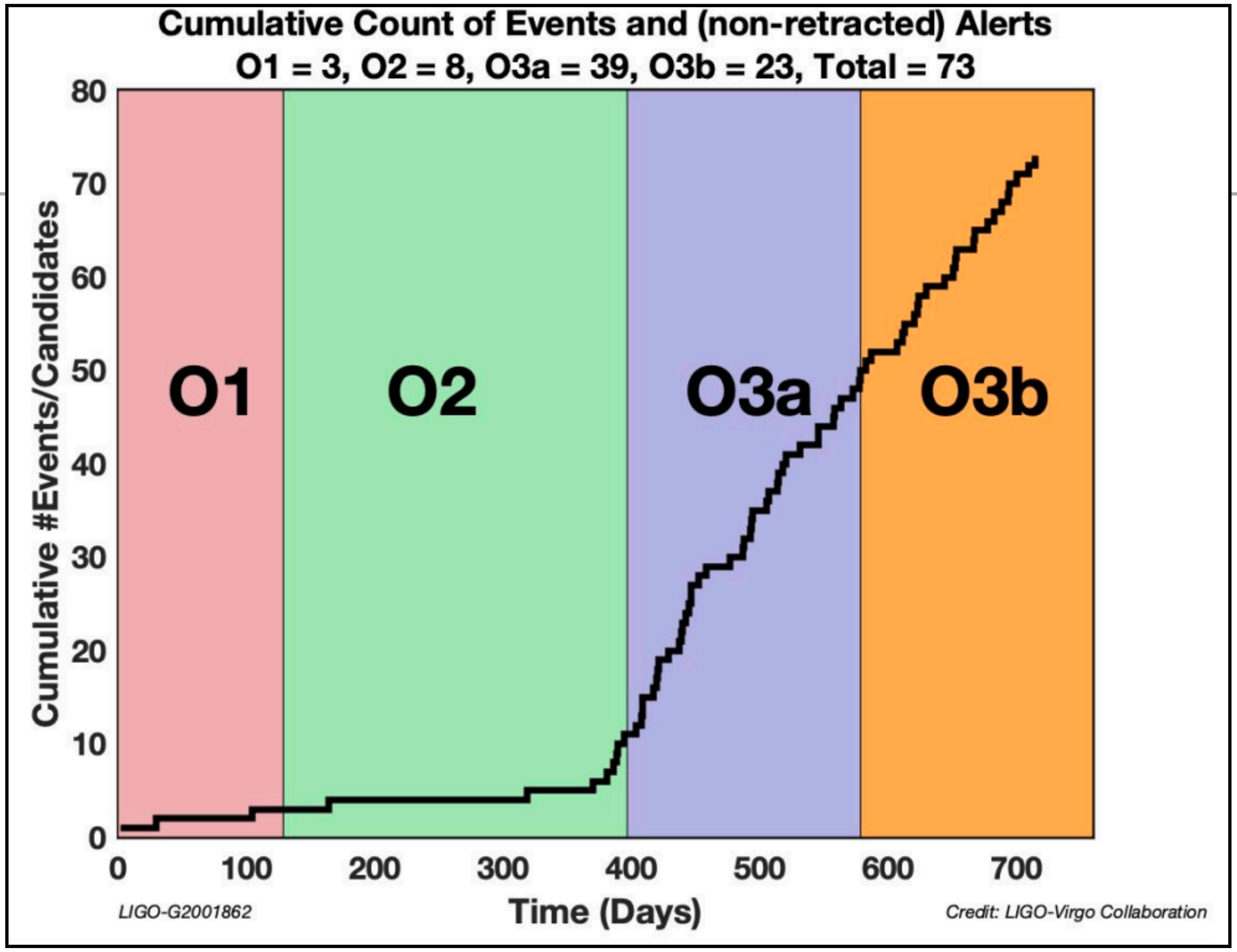


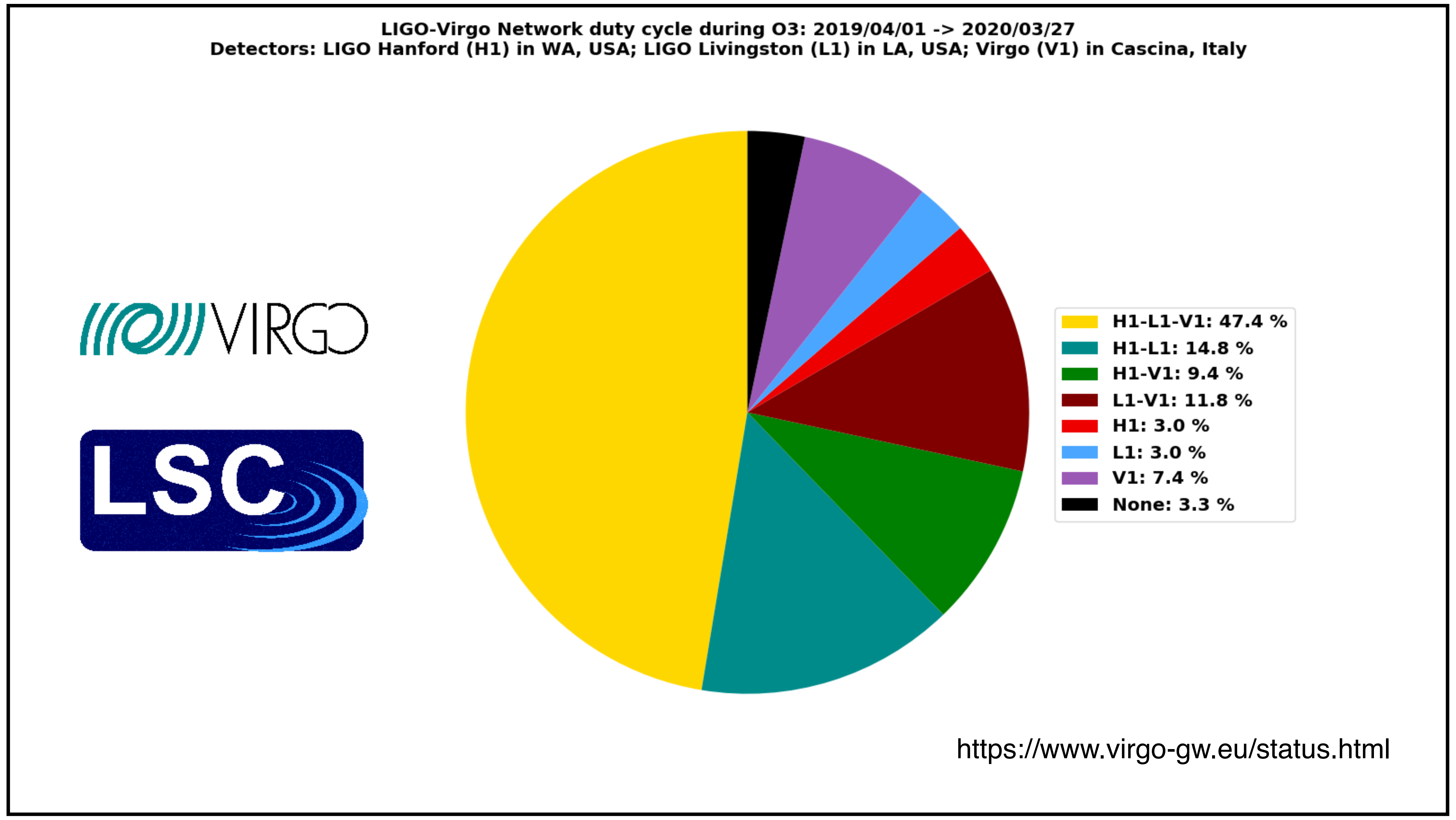
Stochastic background

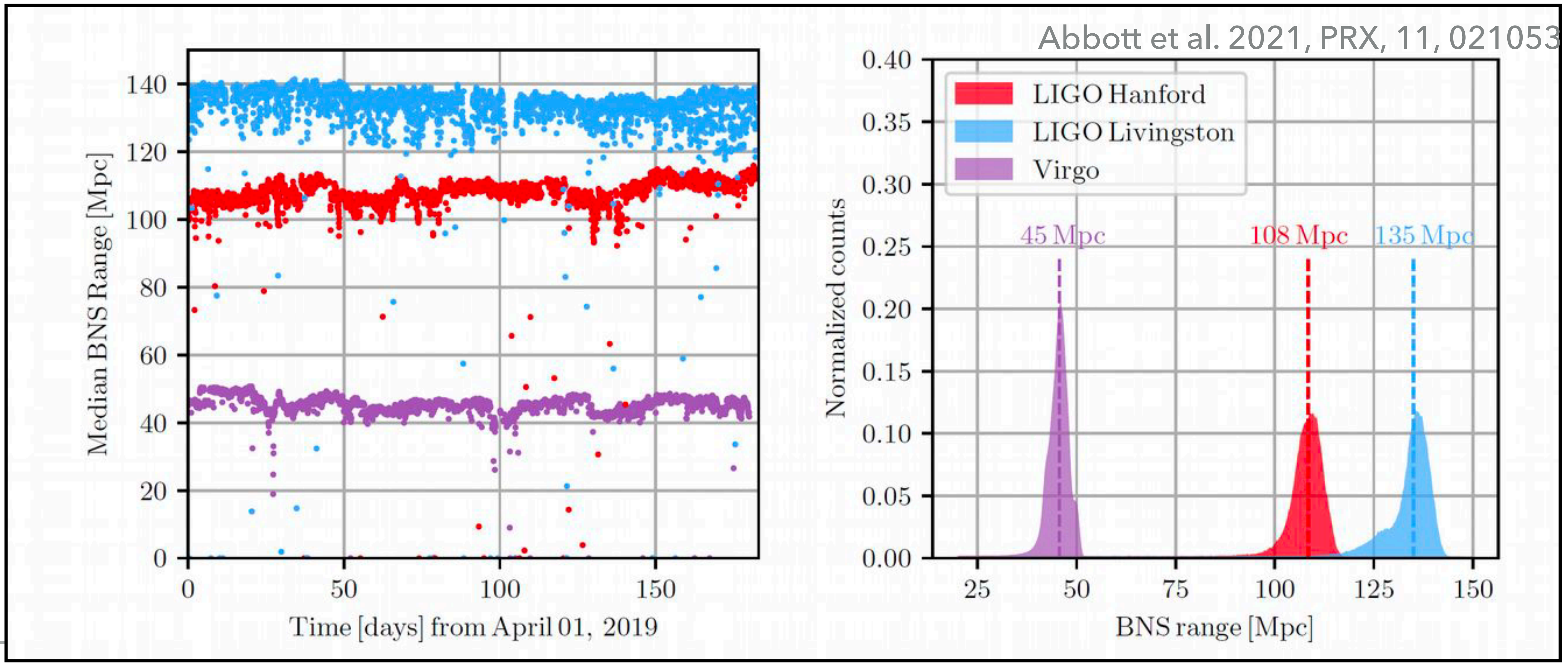


EVENT RATE

- O1 rate $\lesssim$ 1 in a month
- O2 rate ~ 1 in a month
- O3 rate $\gtrsim$ 1 in a week



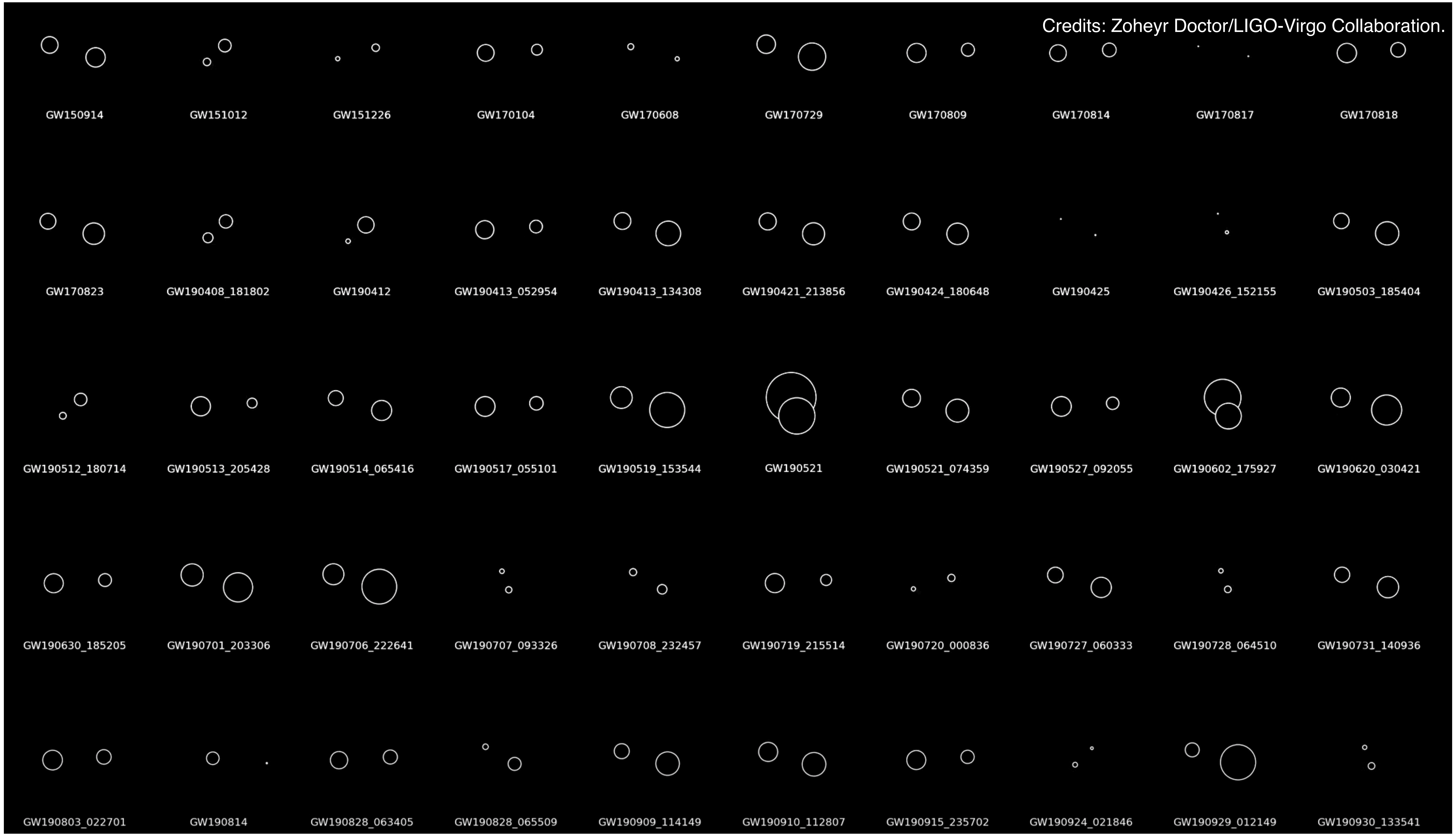




GWTC-2 (O3a)

Abbott et al. 2021, PRX, 11, 021053

- Gravitational Wave Transient Catalog-2
- *false-alarm-rate* < 2 per year
- 39 candidate gravitational-wave events. A contamination fraction expected < 10%.



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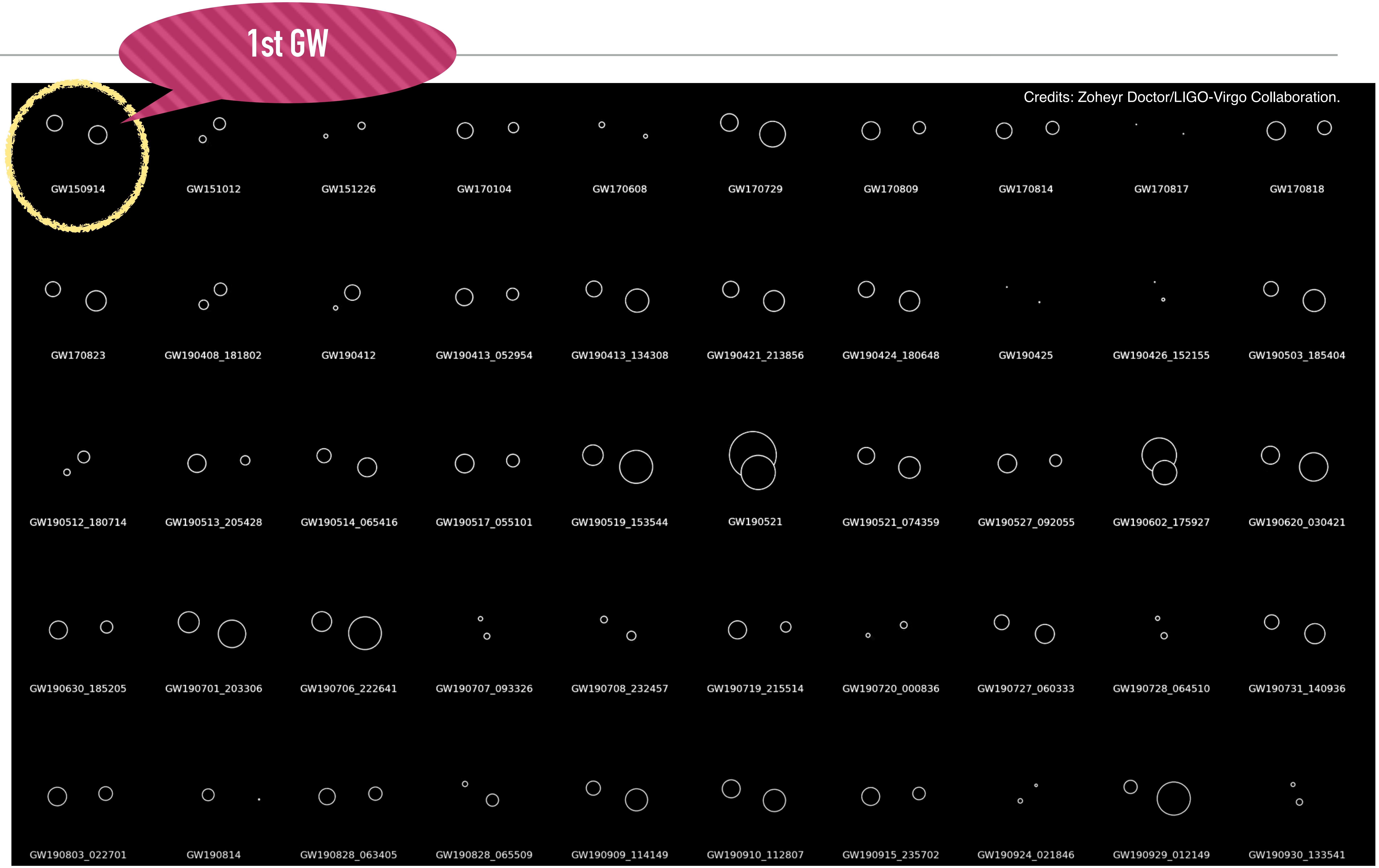

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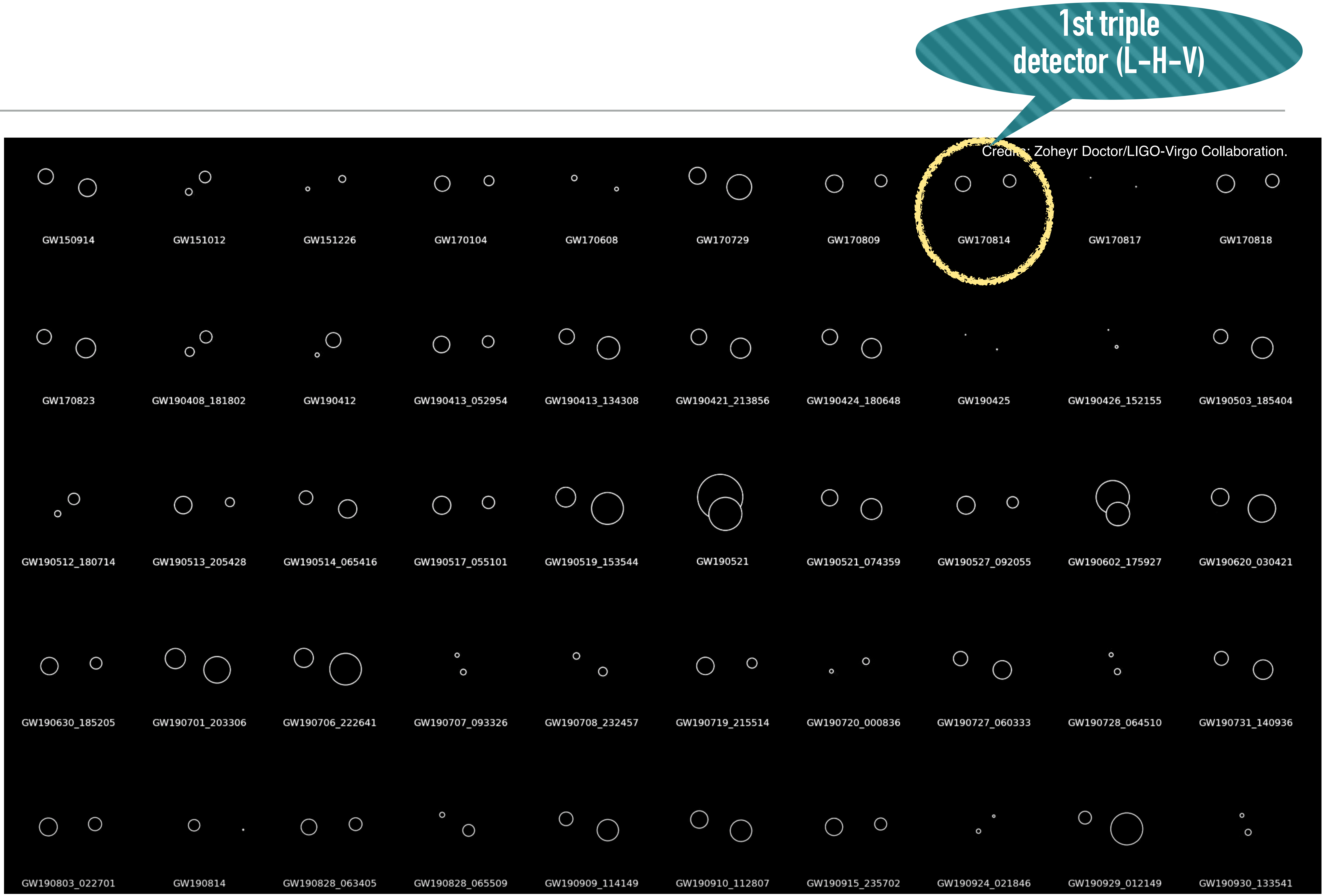

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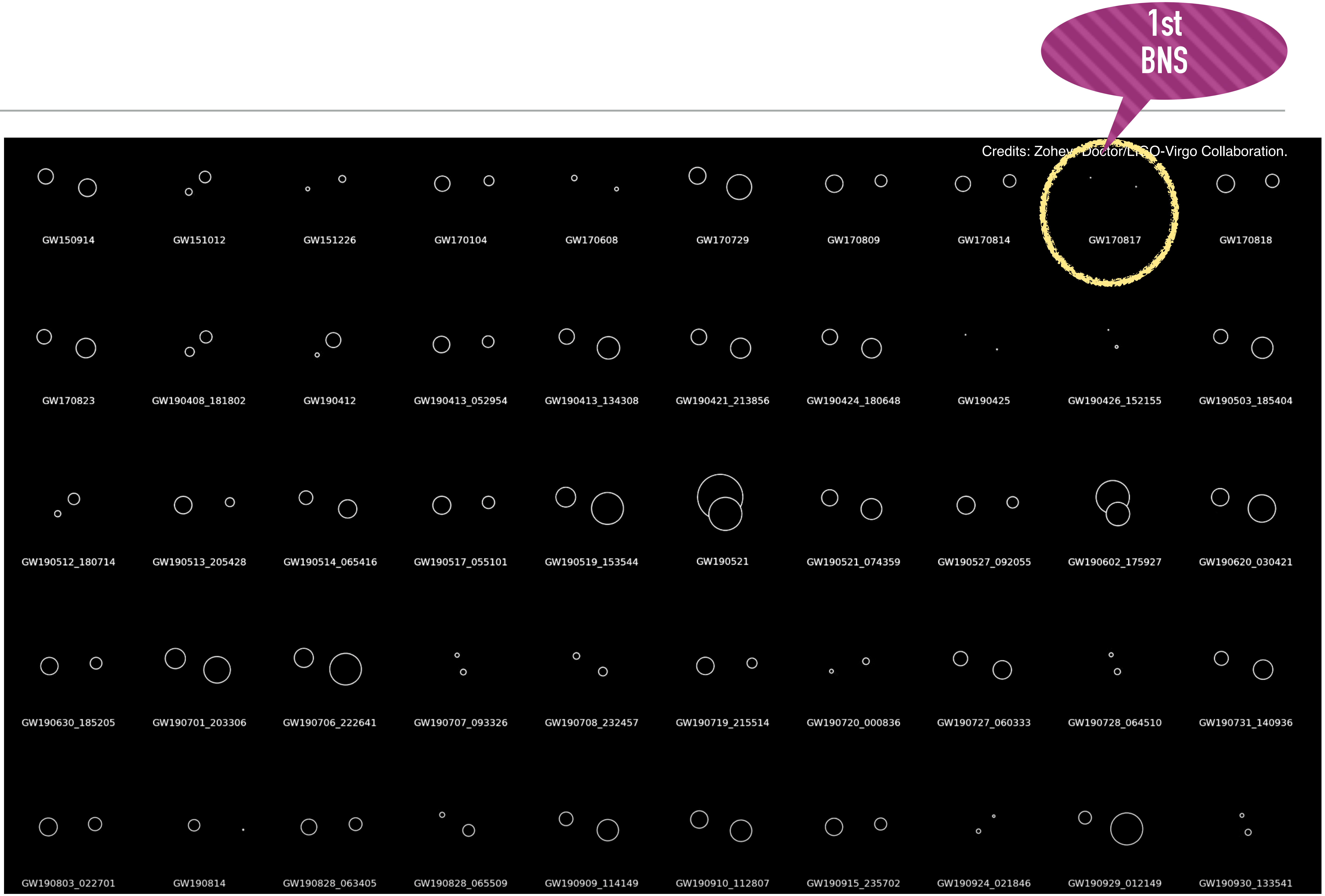

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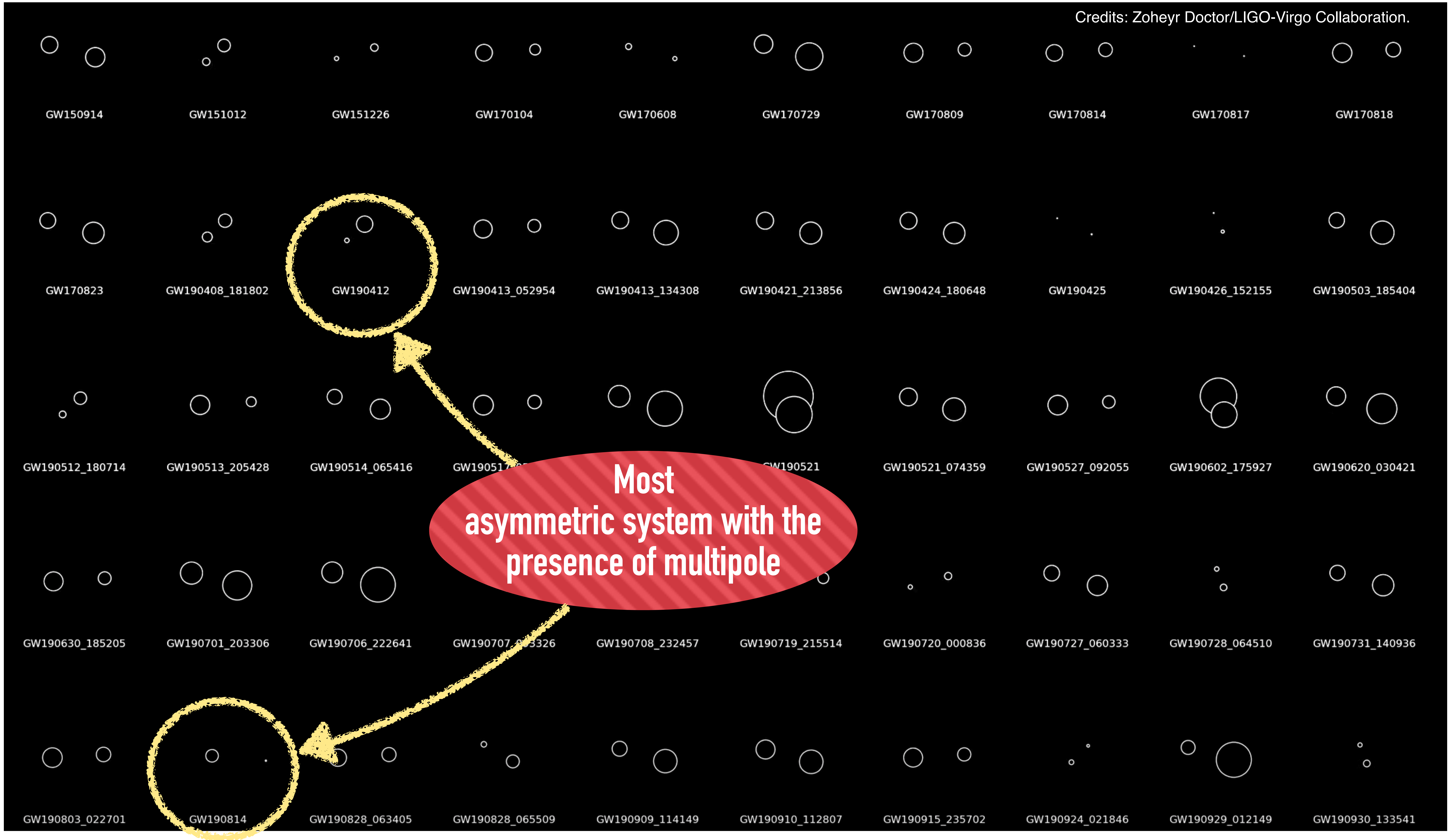

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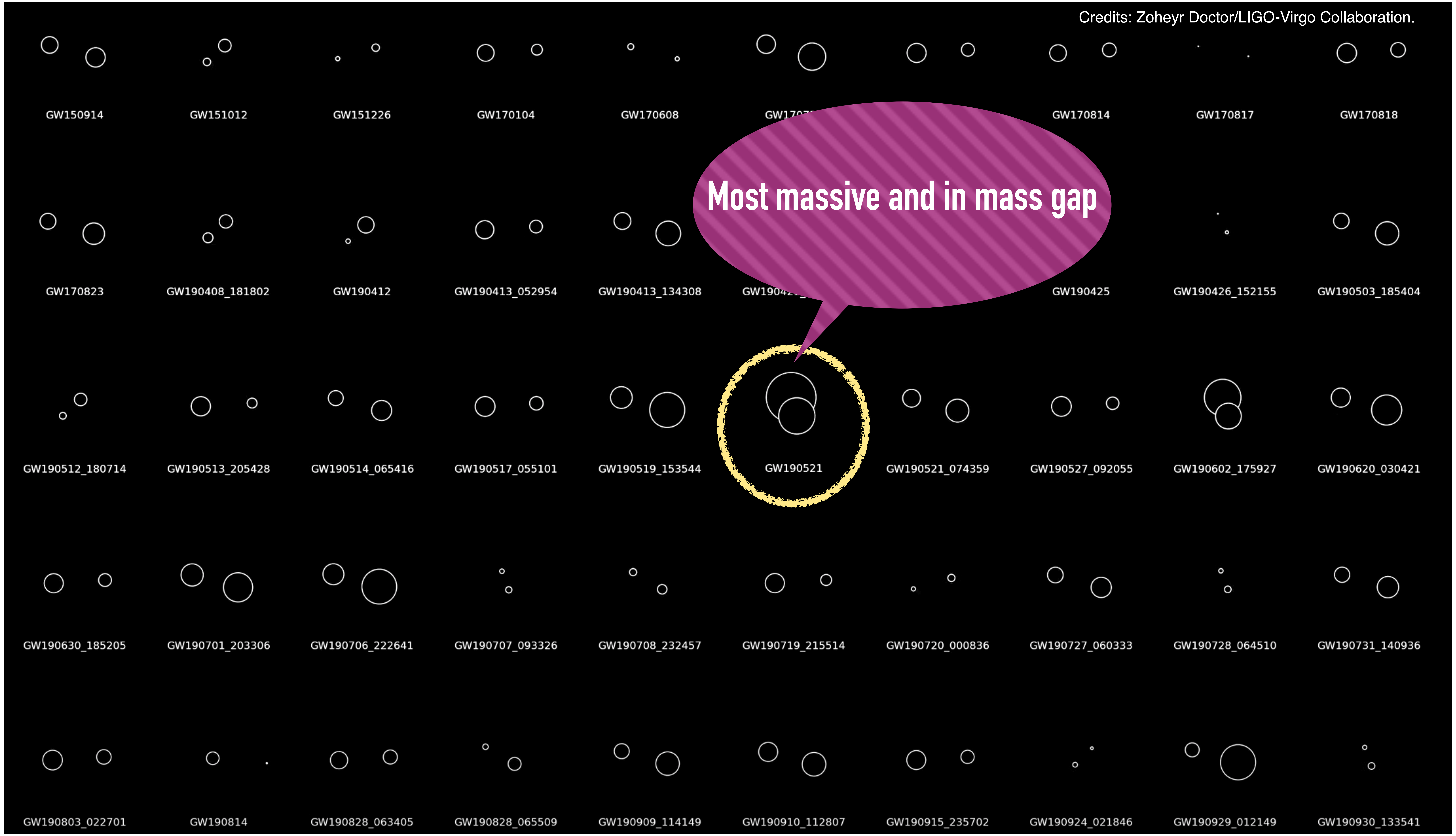

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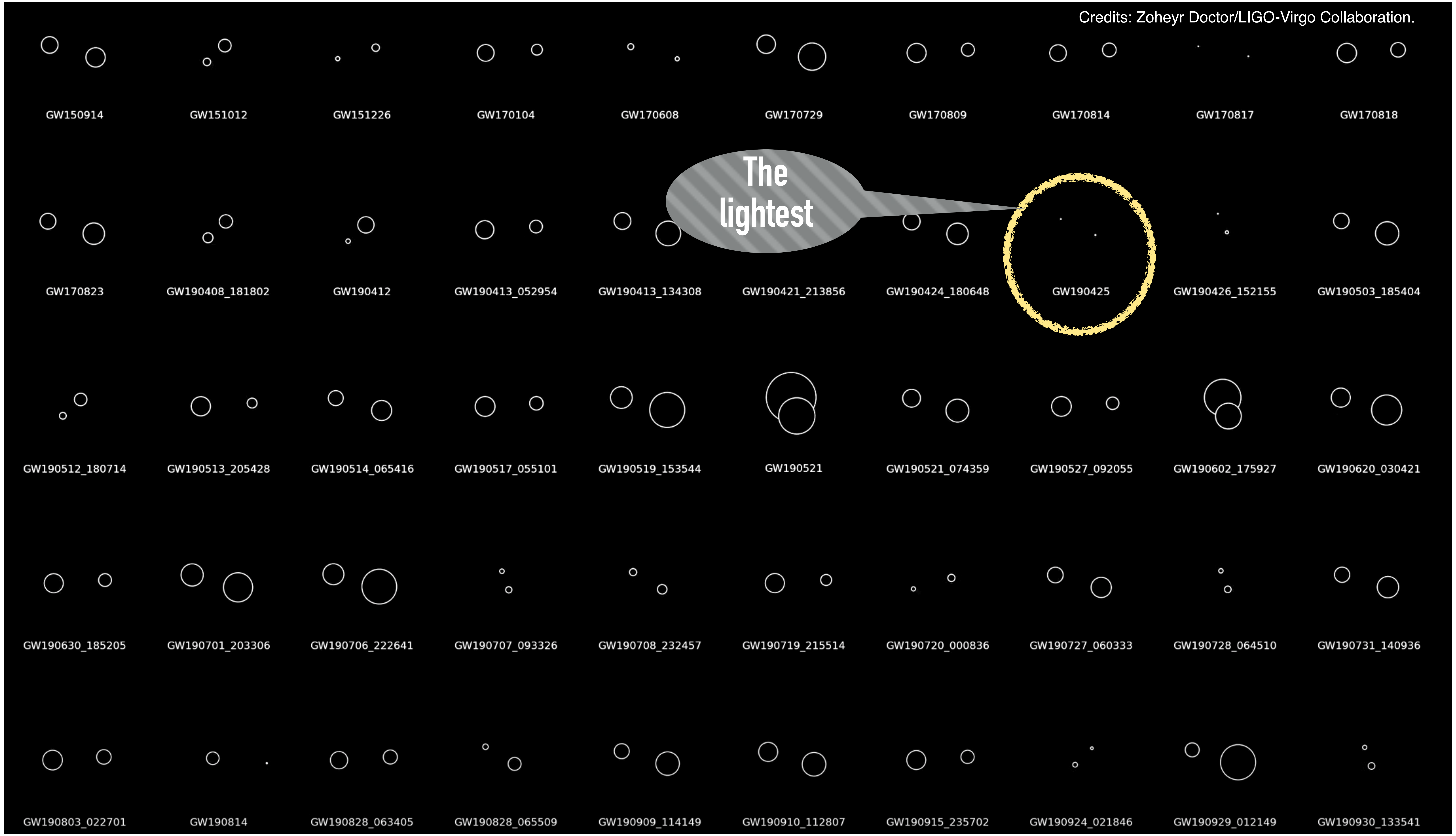


GWTC-2.1

https://arxiv.org/abs/2108.01045

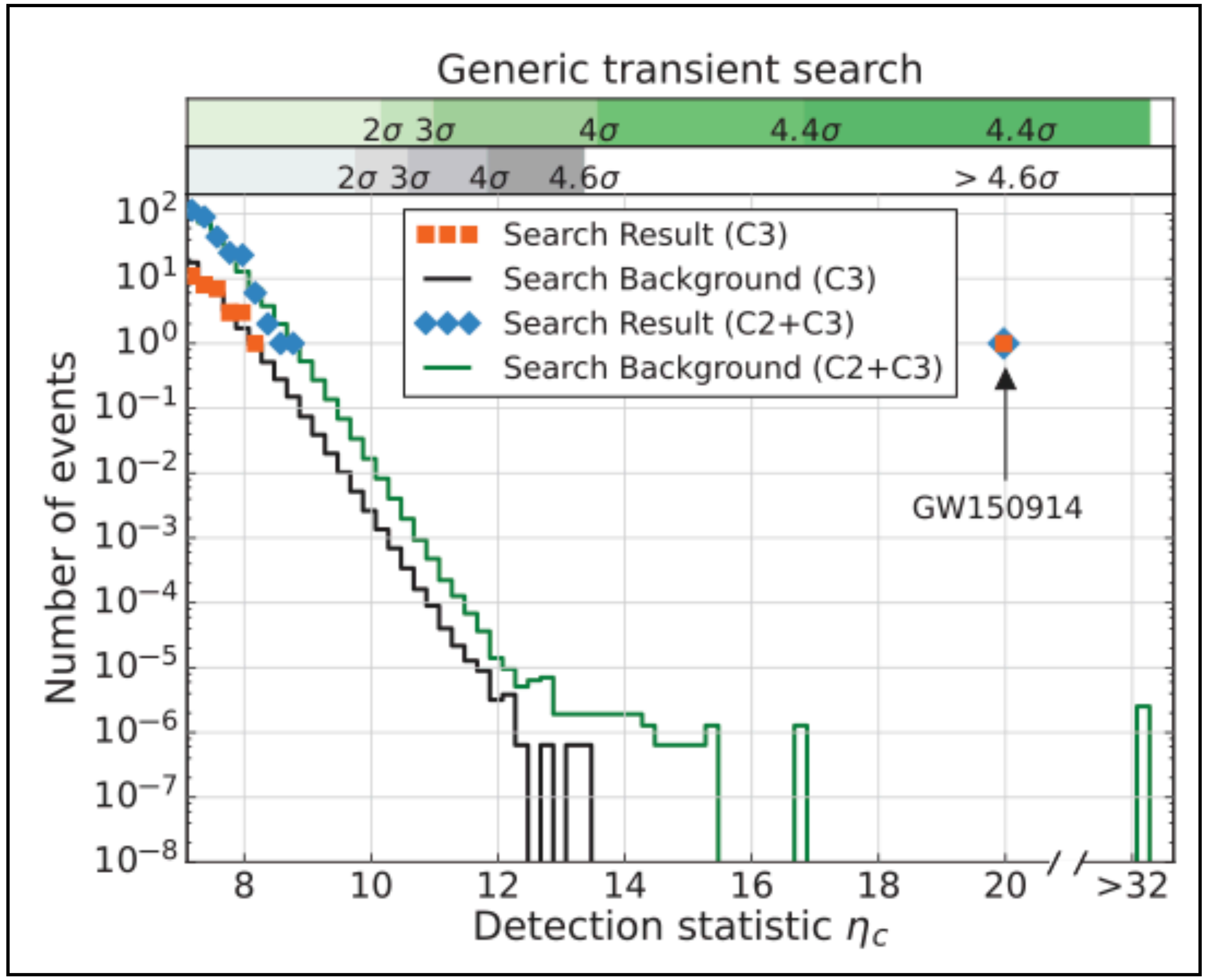
- Deep Extended Catalog of Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run
- Although most of the candidates in this catalog are noise events, they can be used for multimessenger searches by comparing against other astronomical surveys.
- Temporal and spatial coincidences between candidates in distinct astrophysical channels could lead to multimessenger discoveries
- Threshold: FAR<2 per day (instead of 2 per year) ==> 1201 candidates pass these threshold.
- Then, a subset with probability of astrophysical origin ($p_{\rm astro}$) > 0.5 is studied further.
- 8 high-significance additional events more than GWTC2

Event	M ($M_\odot$)	$\mathcal{M}$ ($M_\odot$)	m_1 ($M_\odot$)	m_2 ($M_\odot$)	$\chi_{\rm eff}$	$D_{\rm L}$ (Gpc)	z	$M_{\rm f}$ ($M_\odot$)	$\chi_{\rm f}$	$\Delta\Omega$ (deg^2)
GW190403_051519	$110.5^{+30.6}_{-24.2}$	$36.3^{+14.4}_{-8.8}$	$88.0^{+28.2}_{-32.9}$	$22.1^{+23.8}_{-9.0}$	$0.70^{+0.15}_{-0.27}$	$8.00^{+5.88}_{-3.99}$	$1.14^{+0.64}_{-0.49}$	$105.2^{+29.1}_{-24.1}$	$0.92^{+0.04}_{-0.11}$	5600
GW190426_190642	$184.4^{+41.7}_{-36.6}$	$77.1^{+19.4}_{-17.1}$	$106.9^{+41.6}_{-25.2}$	$76.6^{+26.2}_{-33.6}$	$0.19^{+0.43}_{-0.40}$	$4.35^{+3.35}_{-2.15}$	$0.70^{+0.41}_{-0.30}$	$175.0^{+39.4}_{-34.3}$	$0.76^{+0.15}_{-0.15}$	8200
GW190725_174728	$18.2^{+4.2}_{-1.8}$	$7.4^{+0.6}_{-0.5}$	$11.5^{+6.2}_{-2.7}$	$6.4^{+2.0}_{-2.0}$	$-0.04^{+0.26}_{-0.14}$	$1.05^{+0.57}_{-0.46}$	$0.21^{+0.10}_{-0.09}$	$17.4^{+4.4}_{-1.8}$	$0.65^{+0.08}_{-0.07}$	2300
GW190805_211137	$80.1^{+22.5}_{-16.1}$	$33.5^{+10.1}_{-7.0}$	$48.2^{+17.5}_{-12.5}$	$32.0^{+13.4}_{-11.4}$	$0.35^{+0.30}_{-0.36}$	$5.31^{+4.10}_{-2.95}$	$0.82^{+0.48}_{-0.40}$	$75.8^{+21.2}_{-15.3}$	$0.81^{+0.09}_{-0.15}$	3900
GW190916_200658	$68.9^{+21.0}_{-14.0}$	$27.3^{+9.3}_{-5.5}$	$44.3^{+21.2}_{-13.3}$	$23.9^{+12.7}_{-10.2}$	$0.18^{+0.33}_{-0.29}$	$4.46^{+3.79}_{-2.52}$	$0.71^{+0.46}_{-0.36}$	$65.7^{+19.8}_{-13.4}$	$0.73^{+0.14}_{-0.23}$	4500
GW190917_114630	$11.4^{+3.0}_{-2.9}$	$3.7^{+0.2}_{-0.2}$	$9.3^{+3.4}_{-4.4}$	$2.1^{+1.5}_{-0.5}$	$-0.11^{+0.24}_{-0.49}$	$0.72^{+0.34}_{-0.31}$	$0.15^{+0.06}_{-0.06}$	$11.2^{+3.0}_{-2.9}$	$0.42^{+0.12}_{-0.06}$	2100
GW190925_232845	$37.0^{+3.8}_{-2.6}$	$15.8^{+1.1}_{-1.0}$	$21.2^{+6.9}_{-3.1}$	$15.6^{+2.6}_{-3.6}$	$0.11^{+0.17}_{-0.14}$	$0.93^{+0.38}_{-0.35}$	$0.19^{+0.07}_{-0.07}$	$35.2^{+3.8}_{-2.4}$	$0.72^{+0.07}_{-0.06}$	1200
GW190926_050336	$62.9^{+22.7}_{-11.9}$	$25.6^{+8.8}_{-5.3}$	$39.8^{+20.6}_{-11.1}$	$23.2^{+10.8}_{-9.7}$	$-0.04^{+0.28}_{-0.33}$	$3.78^{+3.17}_{-2.00}$	$0.62^{+0.40}_{-0.29}$	$60.5^{+21.8}_{-11.6}$	$0.65^{+0.14}_{-0.19}$	2500

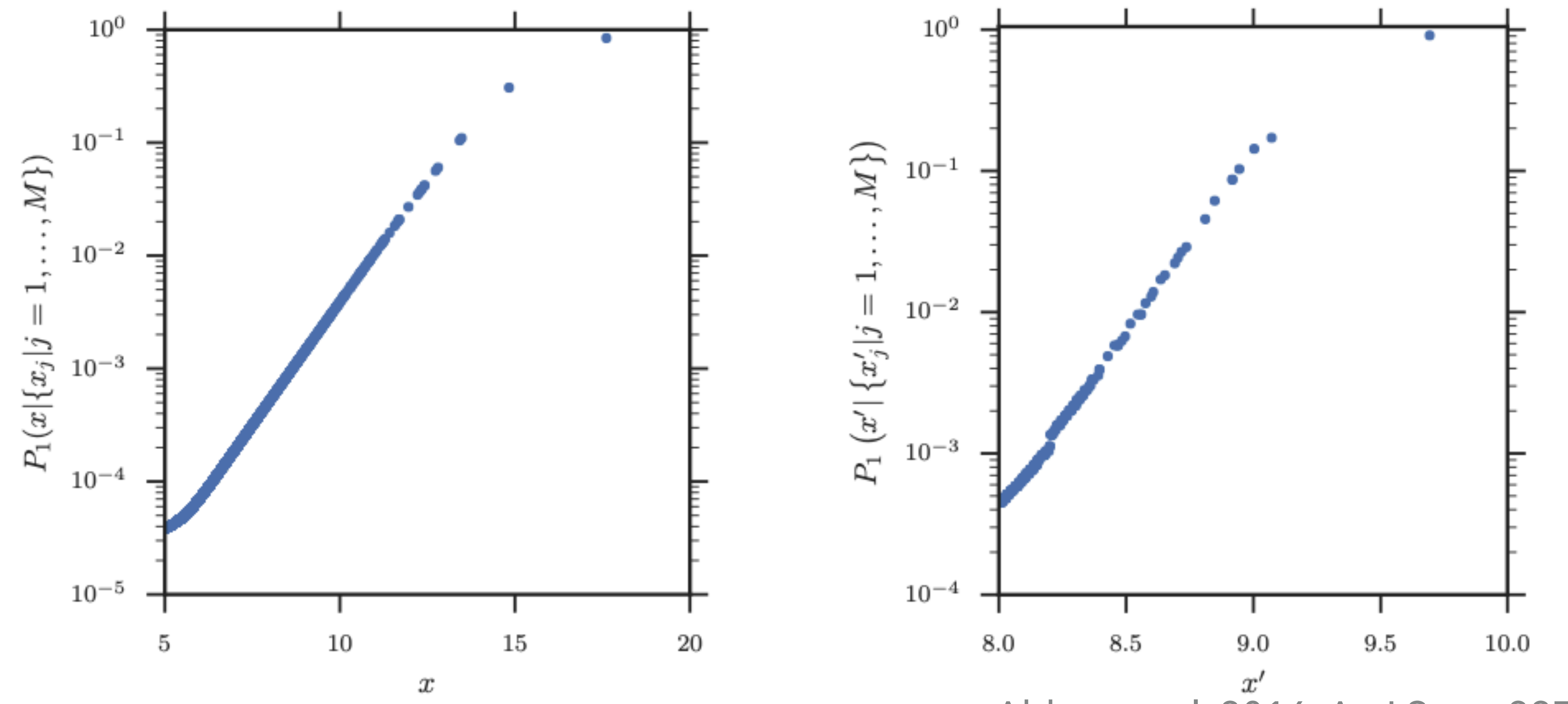
FAR VS P-ASTRO

- FAR: Rate of noise events with a given statistic value (ex: coherent SNR). Some pipelines use timeshift analysis in order to estimate noise distribution

Abbott et al. 2016. PRL 116, 061102



- pAstro (value from 0 to 1) oversimplified: given an assumed signal and terrestrial distribution, we can answer a question of "how likely a trigger belongs to one of these categories".
  - We need to have a robust signal distribution model
  - The more detections we have, the better we can determine the signal-dependent distribution
- Farr et al. 2015. PRD 91 023005; Abbott et al. 2016. ApJ 833 L1; Abbott et al. 2016. ApJ Supp 227 14; Kapadia et al 2020 CQG **37** 045007



Abbott et al. 2016. ApJ Supp 227 14

Figure 6. The posterior probability that coincident triggers in our analysis come from an astrophysical source (see Eq. (7) of the Letter), taking into account the astrophysical and terrestrial expected counts estimated in Section 2.1 of the Letter. Left: the **gstlal** triggers with $x > 5$; right: **pycbc** triggers with $x' > 8$. GW150914 is not shown in the plot because its probability of astrophysical origin is effectively 100%. The only two triggers with $P_1 \gtrsim 50\%$ are GW150914 and LVT151012. For GW150914, we find $P_1 = 1$ to very high precision; for LVT151012, the **gstlal** pipeline finds $P_1 = 0.84$ and the **pycbc** pipeline finds $P_1 = 0.91$.

x, x': detection statistic

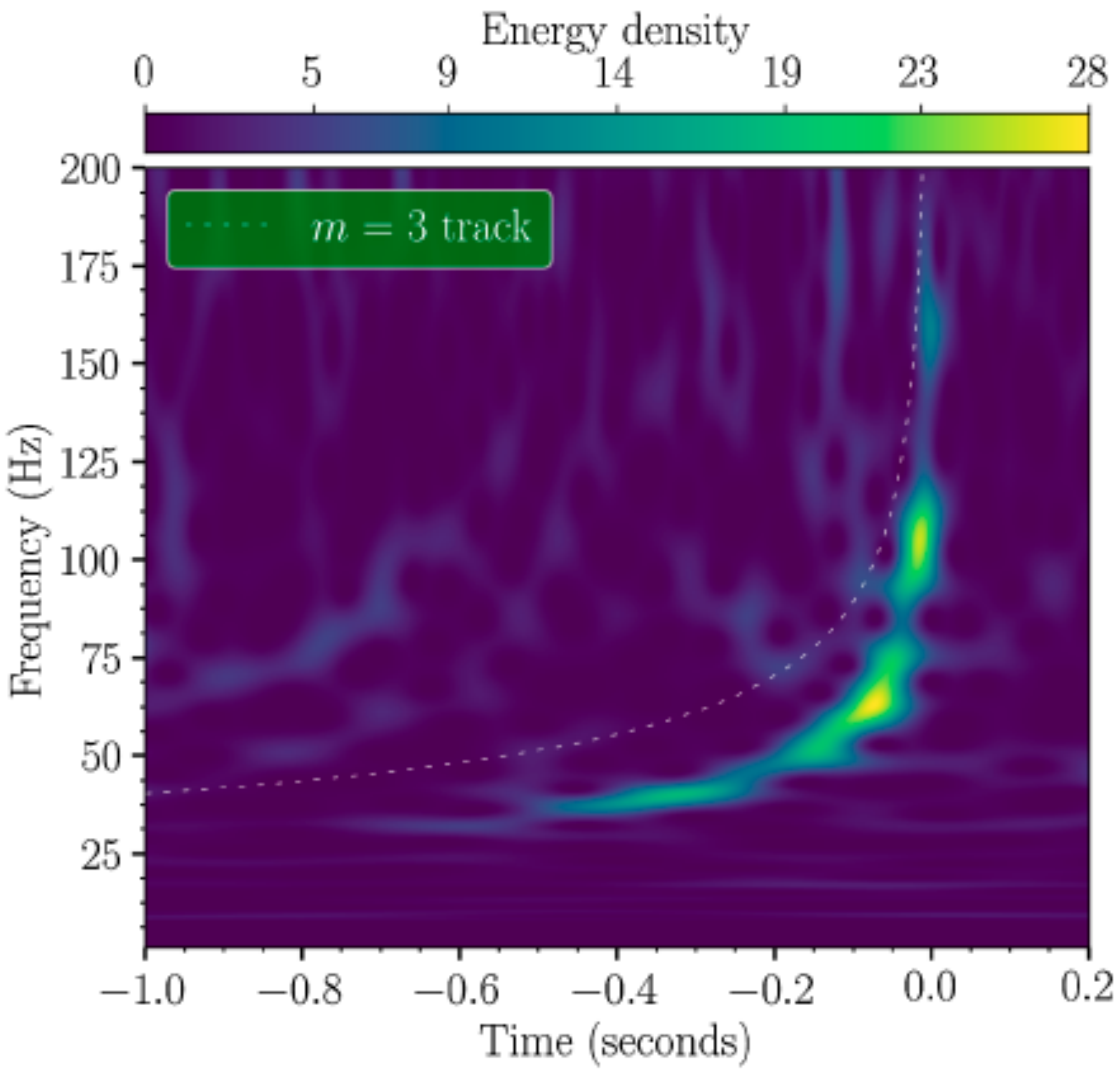
PARTICULAR EVENTS

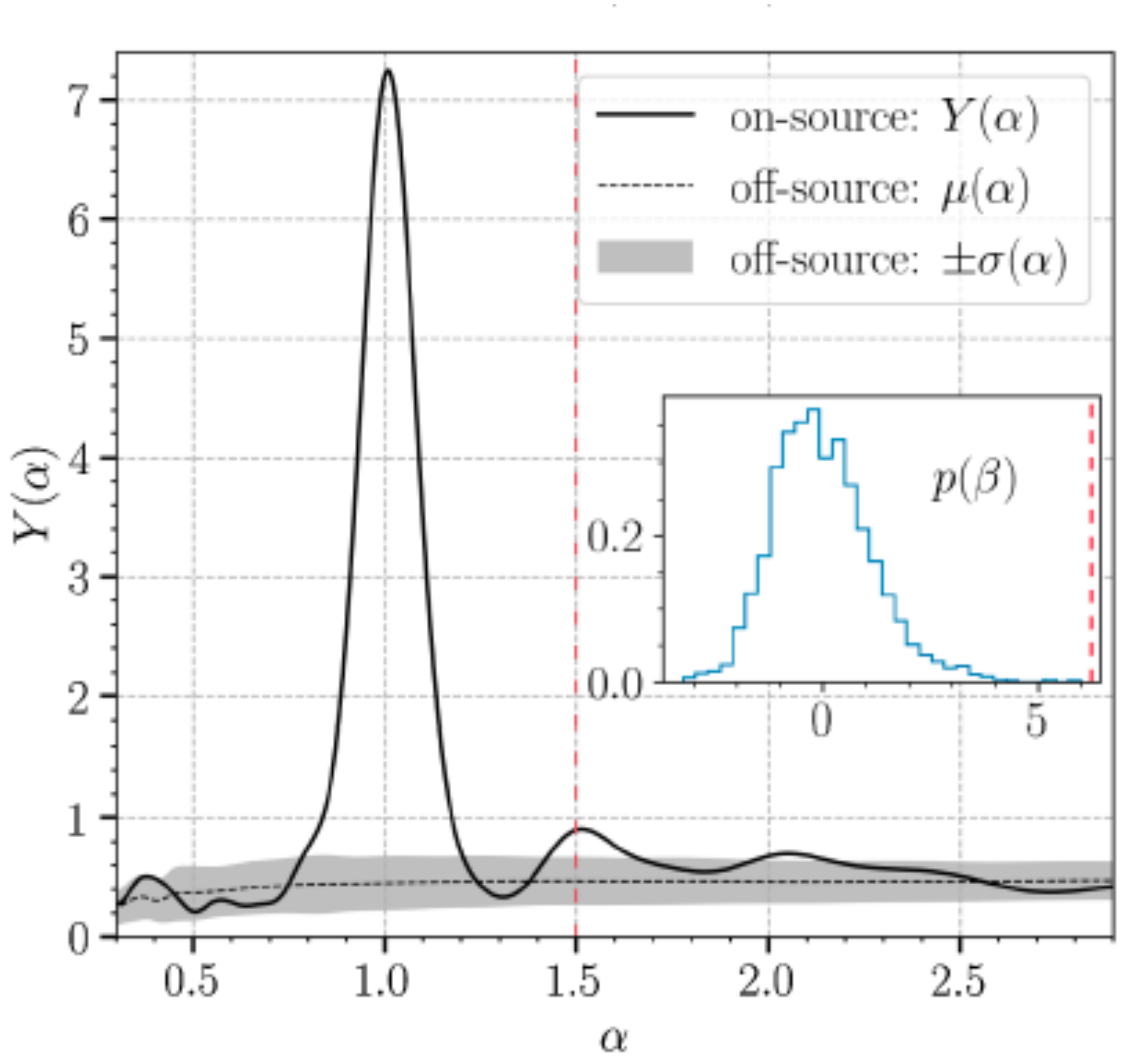
GW190412: ASYMMETRIC-MASS BBH

Abbott et al. 2020. Phys. Rev. D 102, 043015

$$30\,M_\odot + 8\,M_\odot \Rightarrow q \approx 0.28$$

- H-L-V detection
- Asymmetric mass system
- Evidence of higher order multipole
- q value differs from all previous detections, but it is consistent with the population model of stellar BBHs inferred from the first two observing runs.



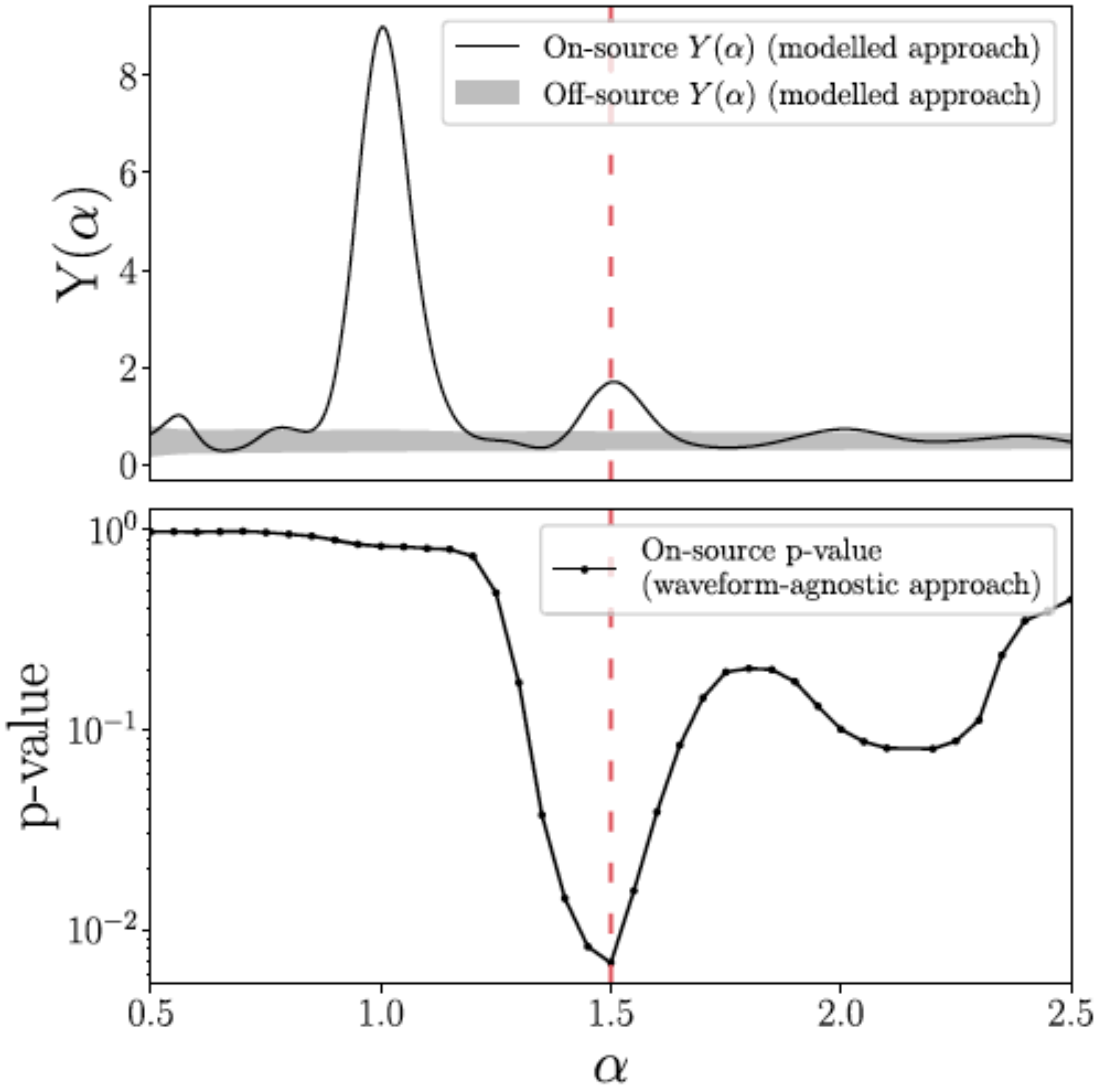


GW190814: ASYMMETRIC-MASS BBH

Abbott et al. 2020. ApJ.L, 896:L44

$$23\,M_\odot + 2.6\,M_\odot \Rightarrow q \approx 0.11$$

- (The most) asymmetric mass system
- Clear evidence of higher order multipole
- m_2 is either the lightest BH or the heaviest NS ever discovered in a double compact-object system
- q, m_1, m_2, and merger rate for this event challenges all current models of the formation and mass distribution of compact-object binaries.



GW190425: A MASSIVE BNS MERGER

B. P. Abbott *et al* 2020 *ApJL* **892** L3

- (Another) BNS merger
- H-L(-V) detection. Virgo has low SNR, but used for parameter estimation
- No EM counterpart
- $m_1 = 1.6 - 2.5\, M_\odot$
- $m_2 = 1.1 - 1.7\, M_\odot$
- $m_{\rm tot} \approx 3.4\, M_\odot;\ \ m_{\rm chirp} \approx 1.44\, M_\odot$
- total mass and the chirp mass are significantly larger than those of any other known binary neutron star (BNS) system
- possibility that one or both binary components of the system are black holes cannot be ruled out from gravitational-wave data

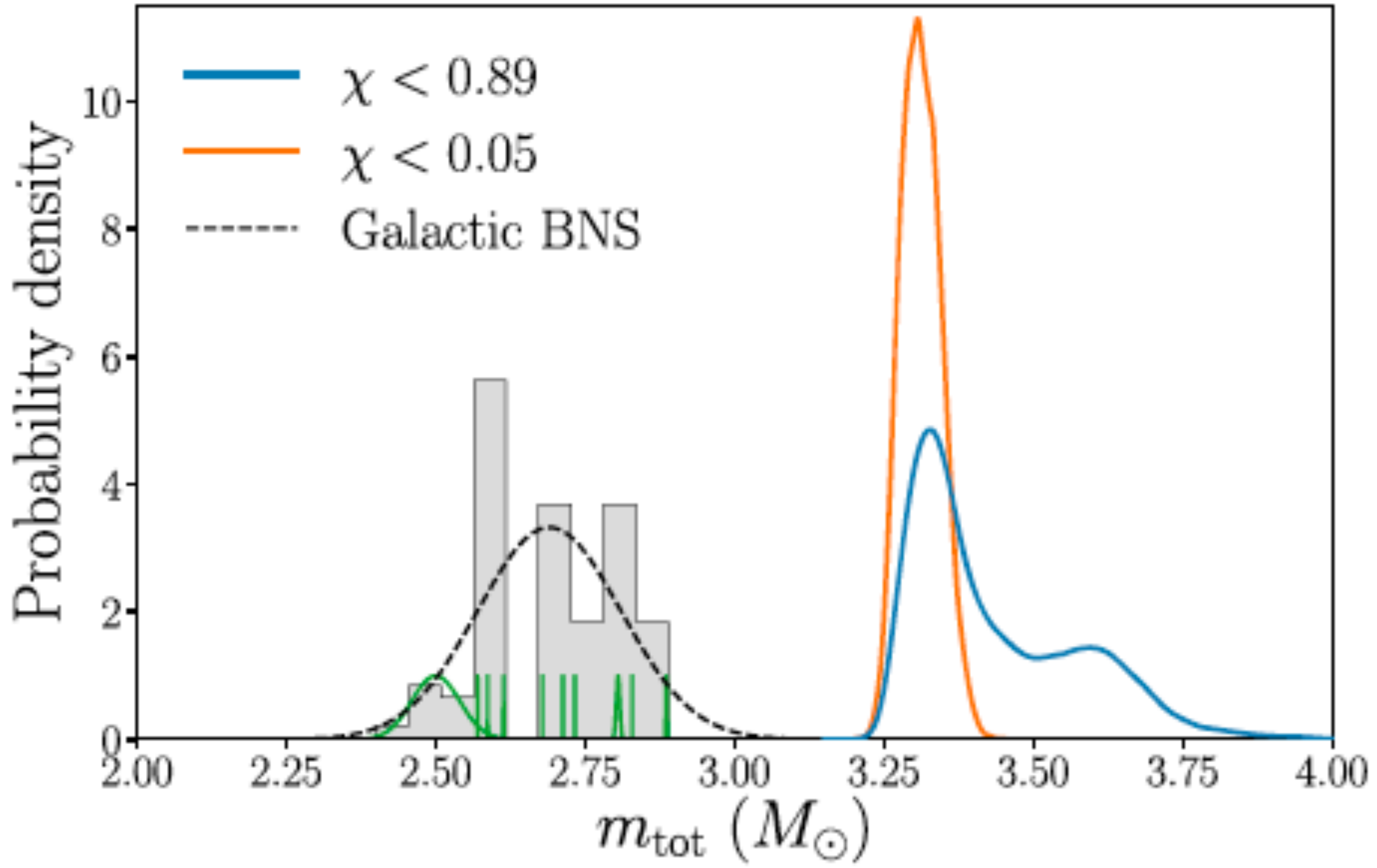
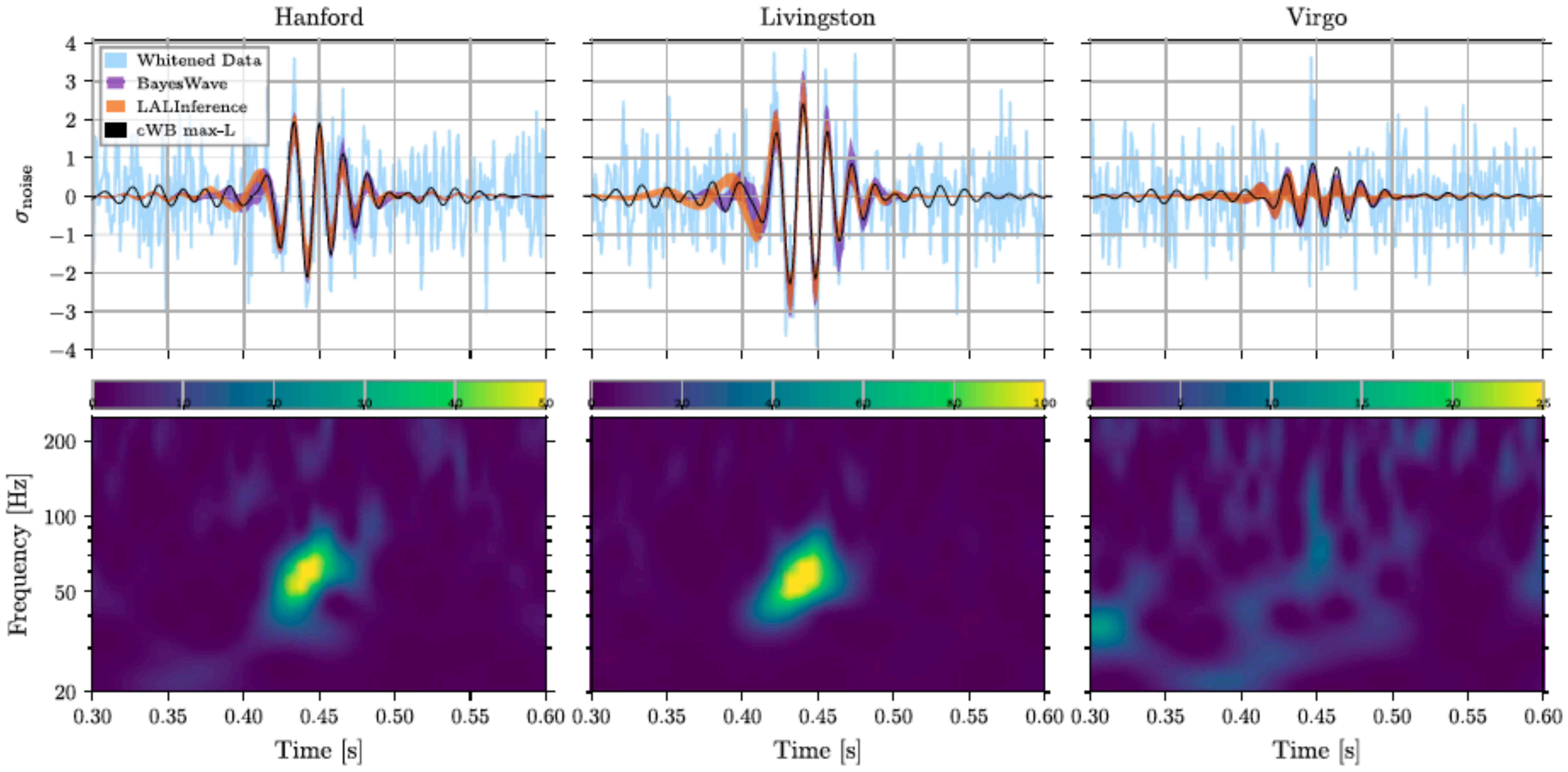


Figure 5. Total system masses for GW190425 under different spin priors, and those for the 10 Galactic BNSs from Farrow et al. (2019) that are expected to merge within a Hubble time. The distribution of the total masses of the latter is shown and fit using a normal distribution shown by the dashed black curve. The green curves are for individual Galactic BNS total mass distributions rescaled to the same ordinate axis height of 1.

GW190521: MOST MASSIVE EVER DETECTED AND IN MASS GAP

Abbott et al. 2020. Phys. Rev. Lett. **125**, 101102

- H-L-V detection
- FAR=1/4900 yr
- $85\,M_\odot + 66\,M_\odot$
- $M_{\rm BH-remnant} \approx 142\,M_\odot$
- Considered to be in a class of Intermediate Mass Blackhole (IMBH); $[10^2\,M_\odot : 10^5\,M_\odot]$
- $D \approx 5.3\,\mathrm{Gpc}$
- $\mathrm{rate} \approx 0.13\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$



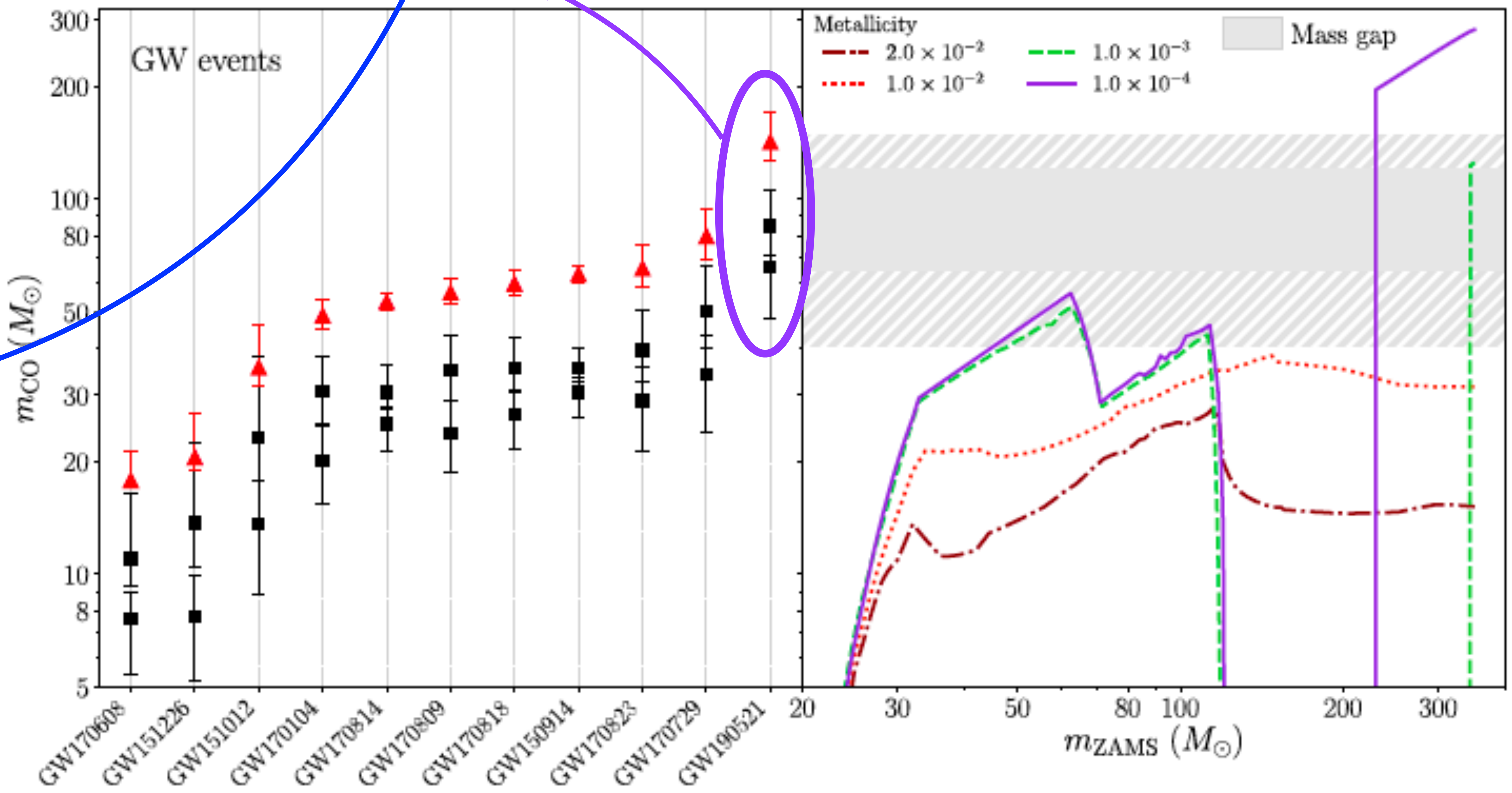
GW190521: MOST MASSIVE EVER DETECTED AND IN MASS GAP

- It is predicted that stars with a helium core mass
  - $\sim 32 - 64\, M_{\odot}$: are subject to pulsational pair instability $\Rightarrow M_{\rm remnant} \lesssim 65\, M_{\odot}$
  - $\sim 64 - 135\, M_{\odot}$: would be susceptible to pair instability and leave **no compact remnant**
  - $\gtrsim 135\, M_{\odot}$: directly collapse to intermediate mass BHs (IMBHs)
- m_1 is under (P)PISN mass gap

$m_2 = [48 : 83]\, M_{\odot}$

$m_1 = [71 : 106]\, M_{\odot}$

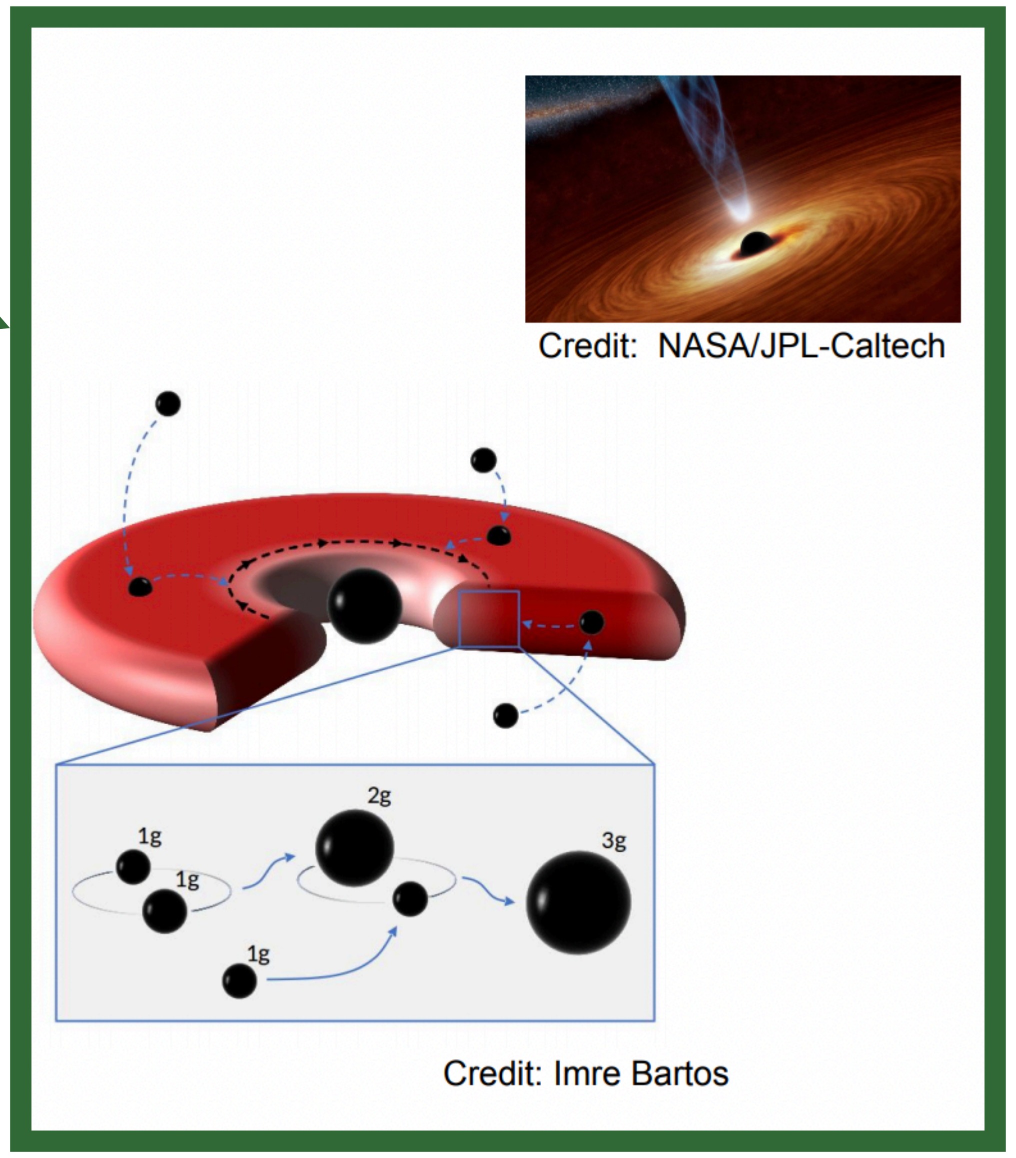
R. Abbott *et al* 2020 *ApJL* **900** L13

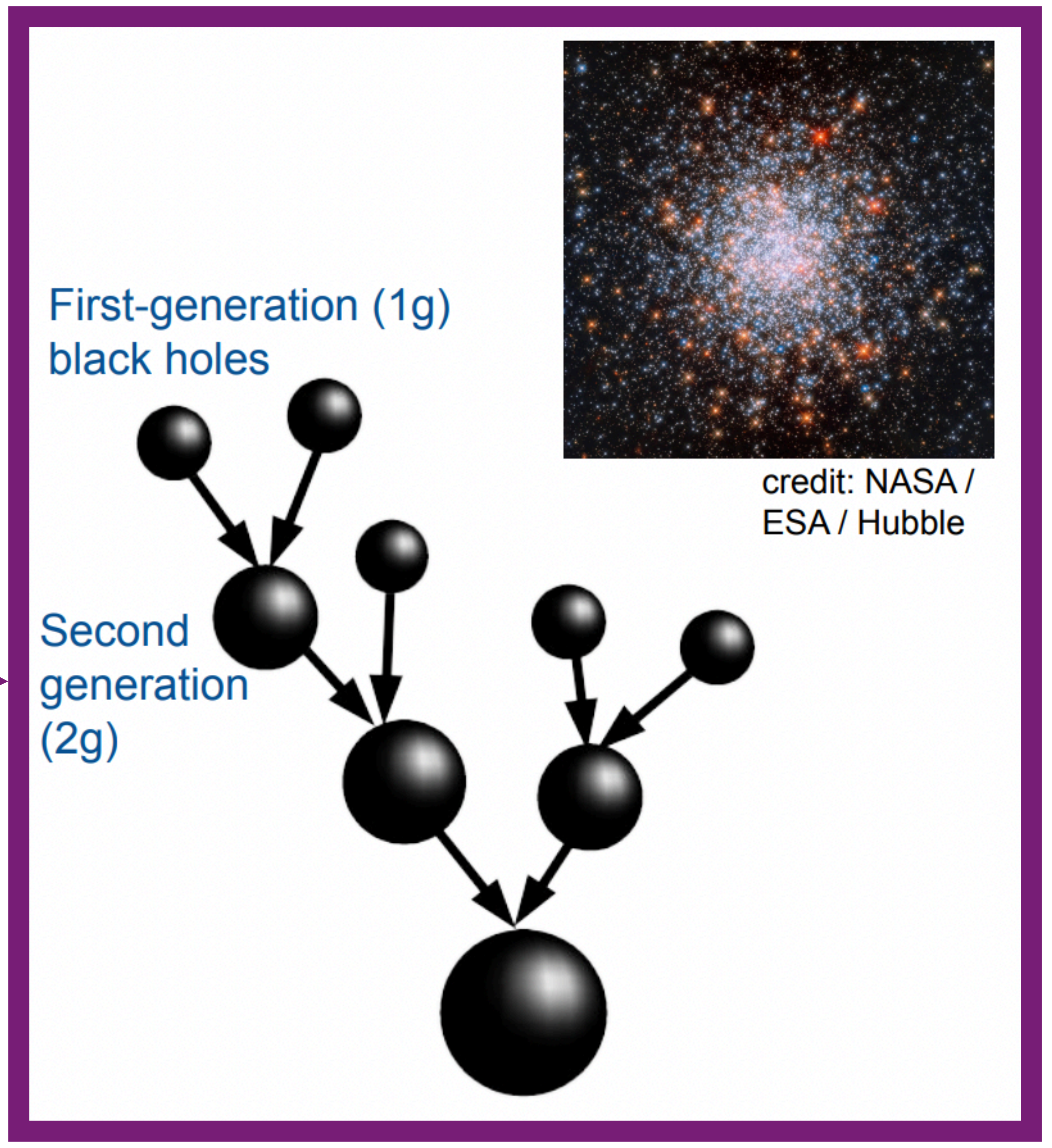


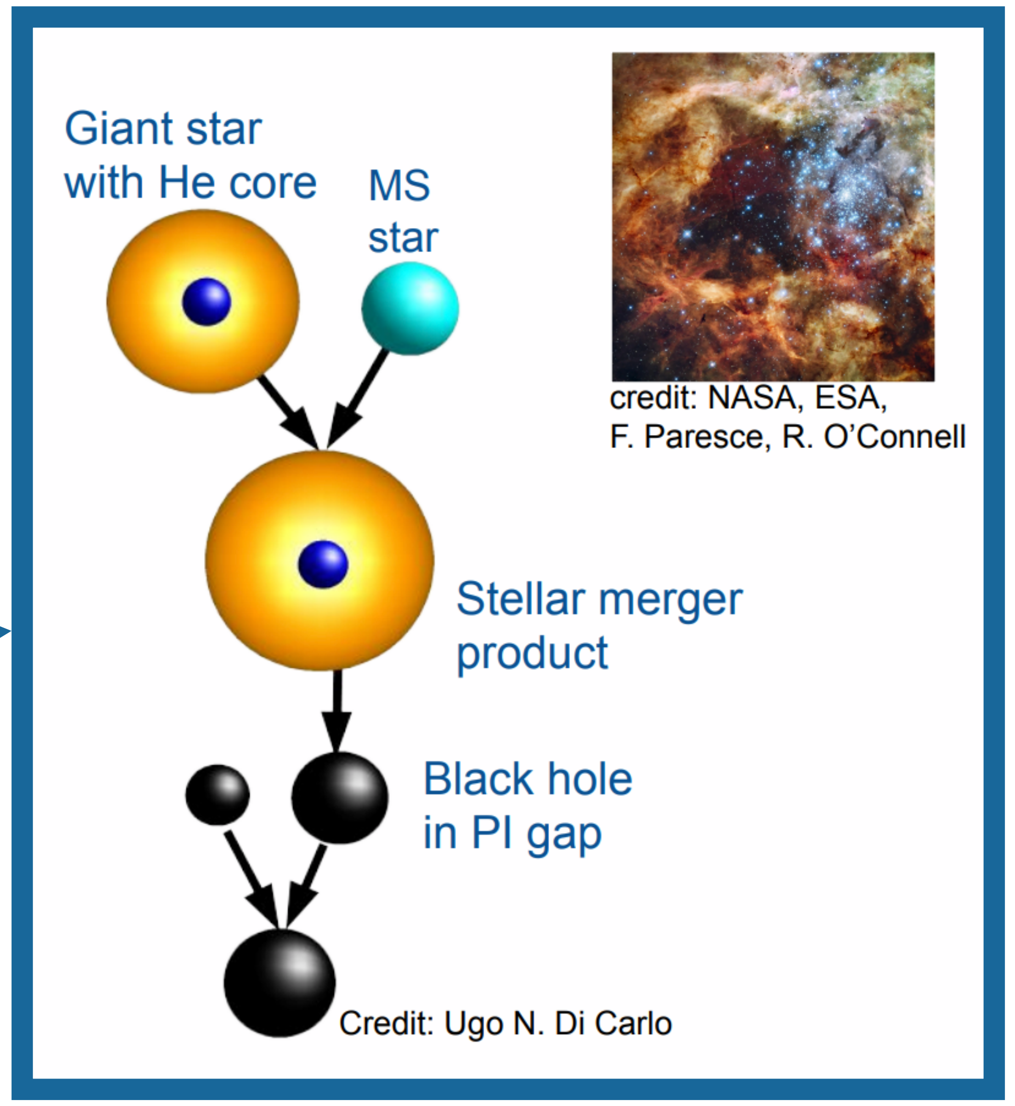
GW190521: MOST MASSIVE EVER DETECTED AND IN MASS GAP

R. Abbott *et al* 2020 *ApJL* **900** L13

- GW190521 may be in dense stellar systems or **AGN disks**.
  - BHs with mass in the PISN gap might form via **hierarchical coalescence** of smaller BHs
  - Or via **direct collapse of the star produced in a stellar merger** between an evolved star and a main sequence companion



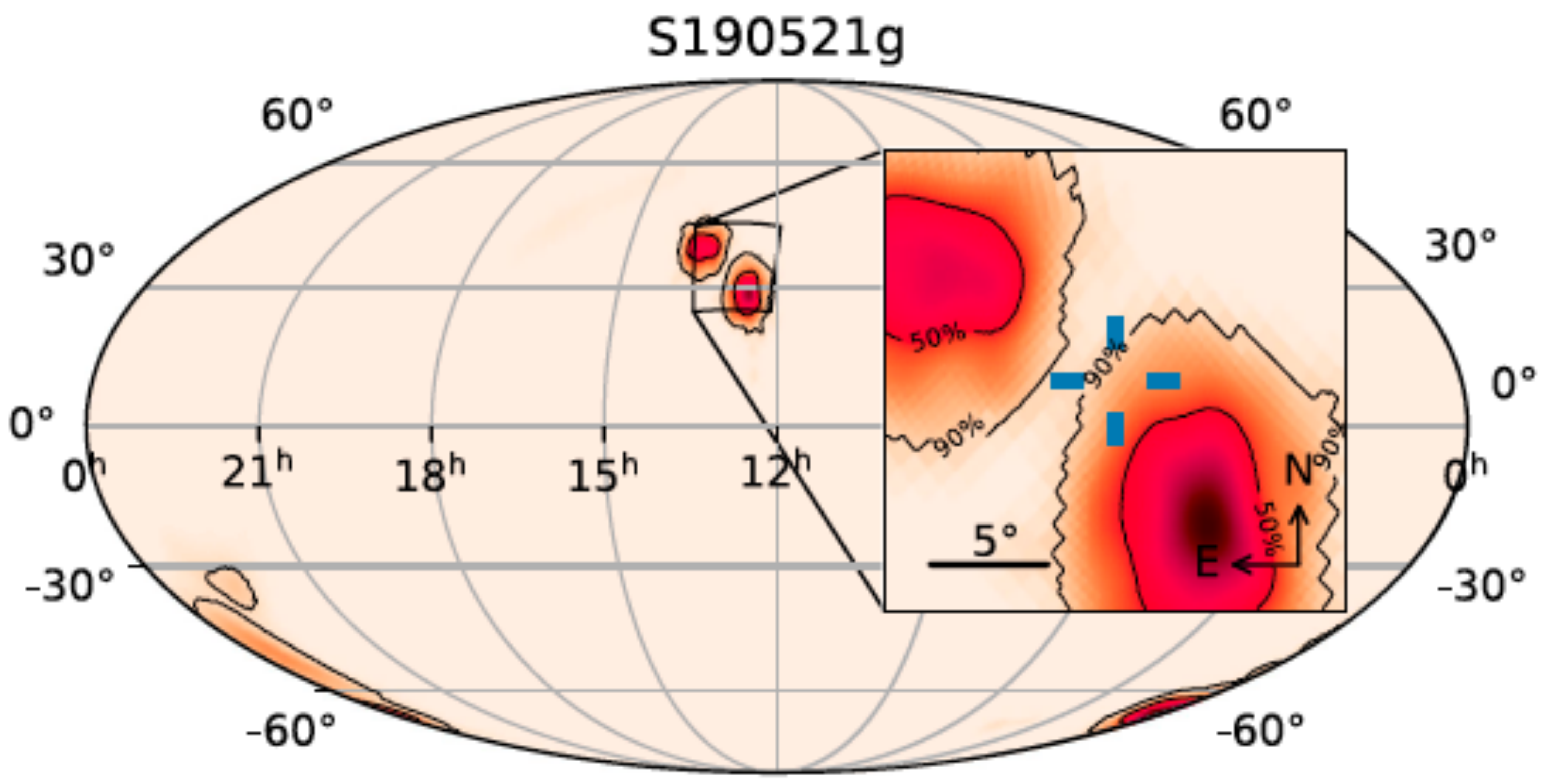


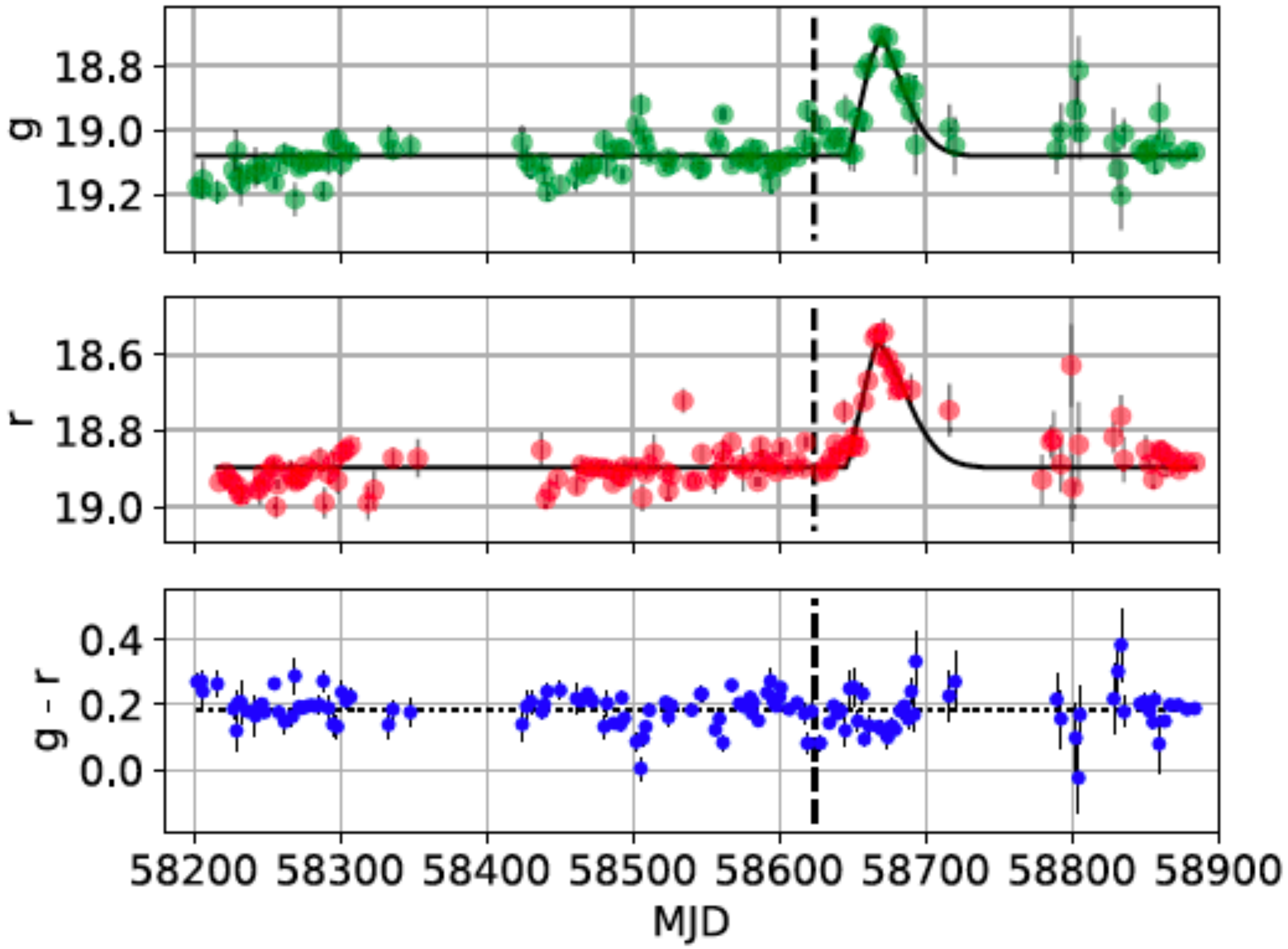


GW190521: MOST MASSIVE EVER DETECTED AND IN MASS GAP

- BBH in the accretion disk of SMBH?
- EM flare close to AGN ~ 34 days after the GW190521
- Consistent with expectations for a kicked BBH merger in the accretion disk AGN

Graham et al. 2020, PRL 124, 251102

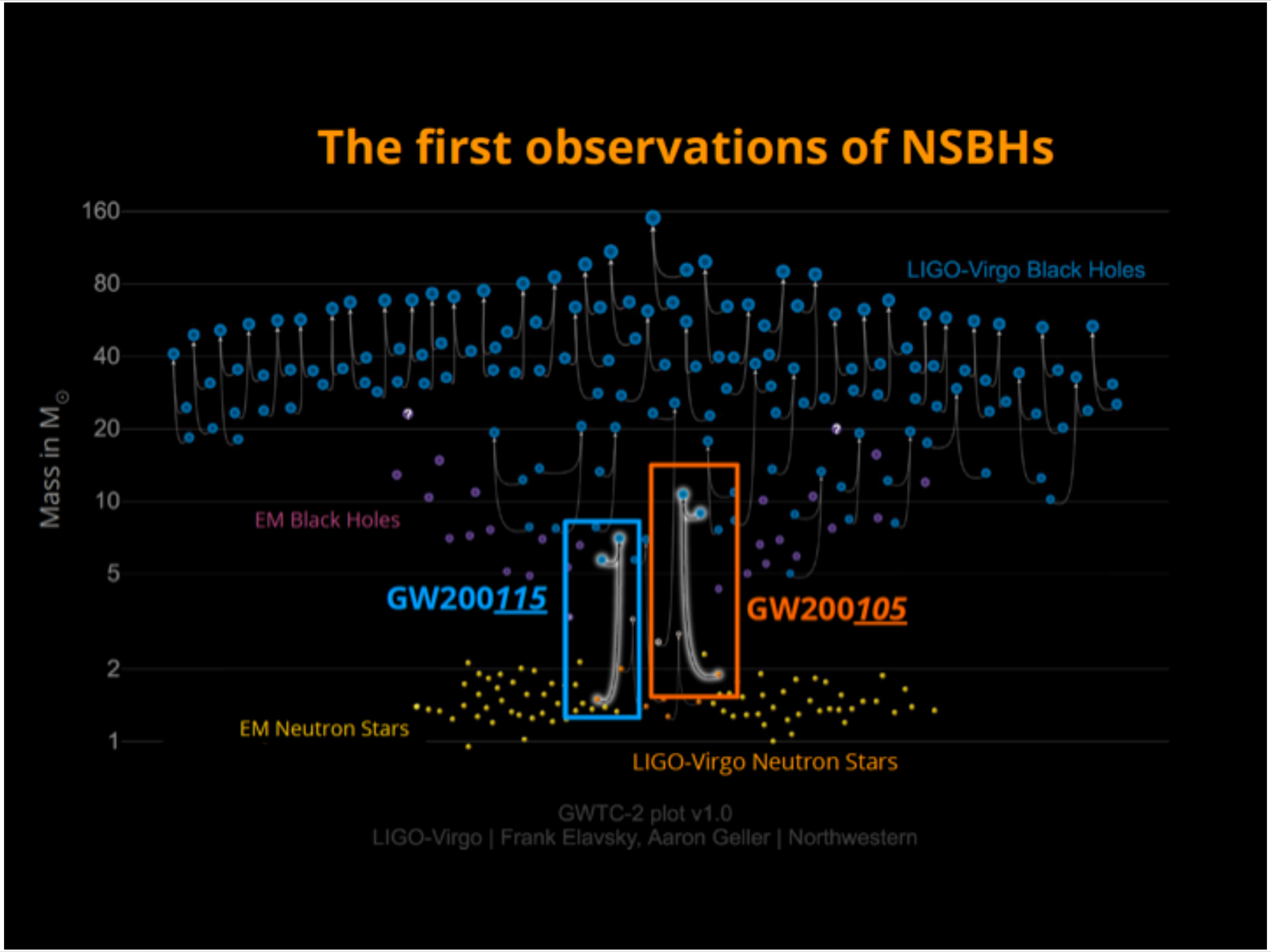




ZTF g, r, g-r band photometry

NSBH IN O3b (GWTC-3)

R. Abbott *et al* 2021 *ApJL* **915** L5

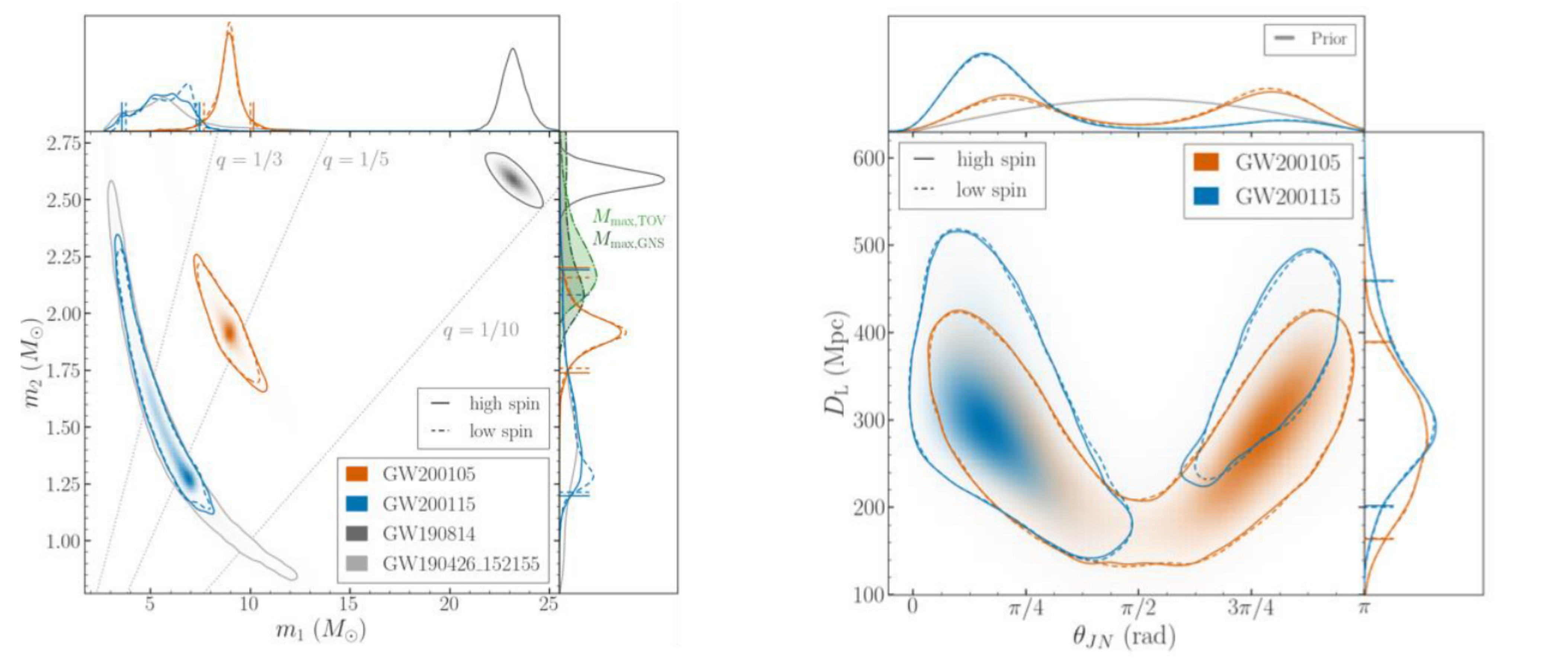


NSBH IN O3b (GWTC-3)

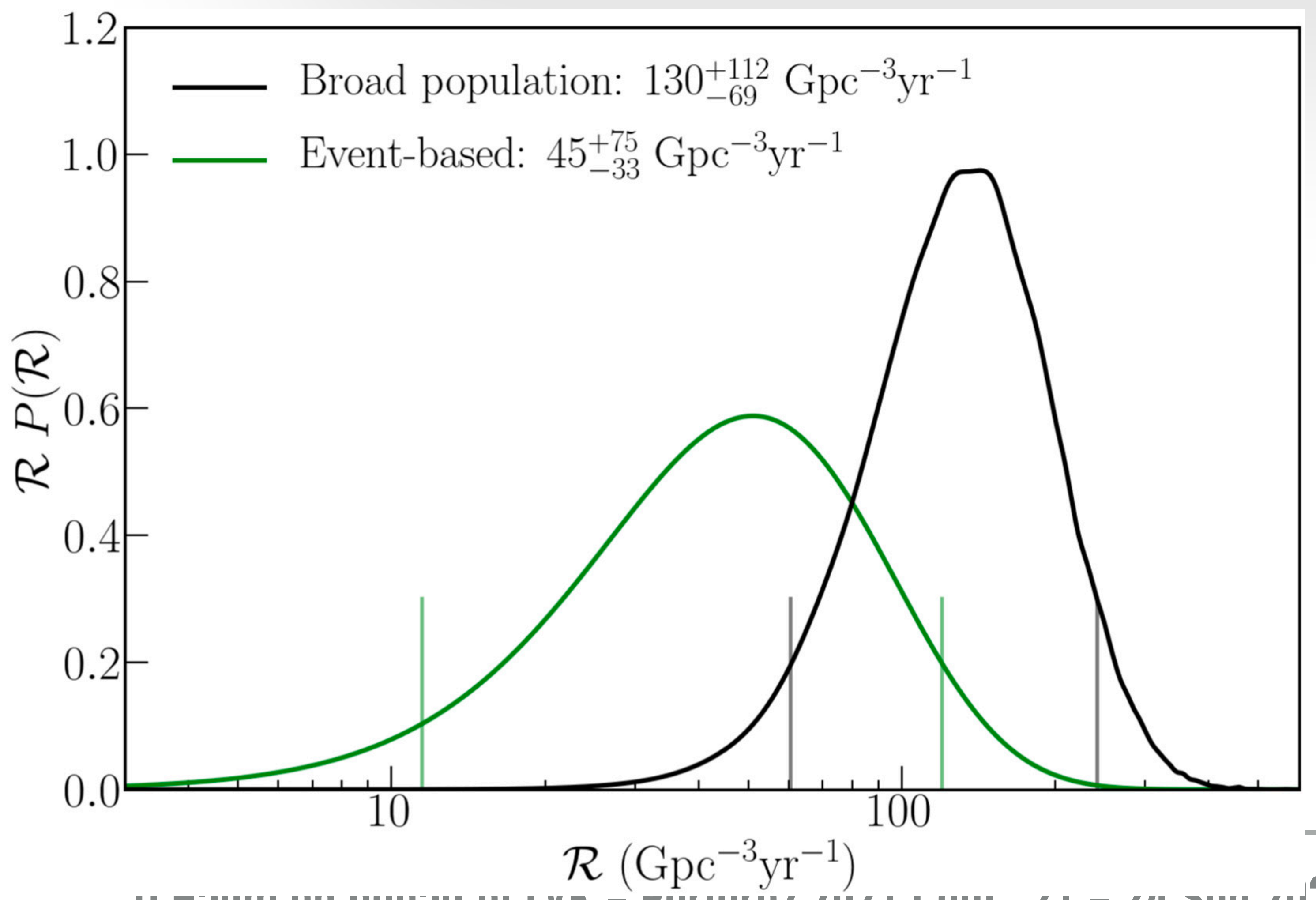
R. Abbott *et al* 2021 *ApJL* **915** L5

- No EM counterpart (expected due to the absence of ejecta as well as large distance + large uncertainty of sky position)

Images: companion masses (left), distance vs inclination (right), both with low (<0.05) and high (<0.99) spin priors for the neutron stars



Credits: B.S. Sathyaprakash, Penn State and Cardiff University



- Event based (assuming one count each from these events): $12 - 120\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- Broad population rate (including less significant triggers in O1, O2, and O3): $61 - 242\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

FACT SHEET

GW200105 GW200115

First observation of neutron star-black hole (NSBH) binaries

All parameter ranges correspond to 90% credible bounds. Quoted values are for high spin (<0.99) neutron-star priors

	GW200105	GW200115
observed by	LIGO Livingston and Virgo	LIGO Livingston & Hanford and Virgo
date, time	5 Jan 2020, 16:24:26 UTC	15 Jan 2020, 04:23:10 UTC
likely distance	170 to 390 Mpc	200 to 450 Mpc
source redshift	0.04 to 0.08	0.05 to 0.10
signal-to-noise ratio	13.9	11.6
false alarm rate	< 1 in 2.8 yr	< 1 in 100,000 yr
Source masses ($M_\odot$)		
total mass	9.7 to 12.0	5.7 to 8.6
primary (BH)	7.4 to 10.1	3.6 to 7.5
secondary (NS)	1.7 to 2.2	1.2 to 2.2
mass ratio	0.18 to 0.30	0.16 to 0.61
BH spin	0.00 to 0.30	0.04 to 0.81
effective inspiral spin	−0.16 to 0.10	−0.54 to 0.04
effective precession spin	0.02 to 0.23	0.04 to 0.51

Inferred merger rate density of NSBH systems*: 12 to 120 yr^{-1} Gpc^{-3}

* Assuming GW200105 and GW200115 Credits: B.S. Sathyaprakash, Penn State and Cardiff University.

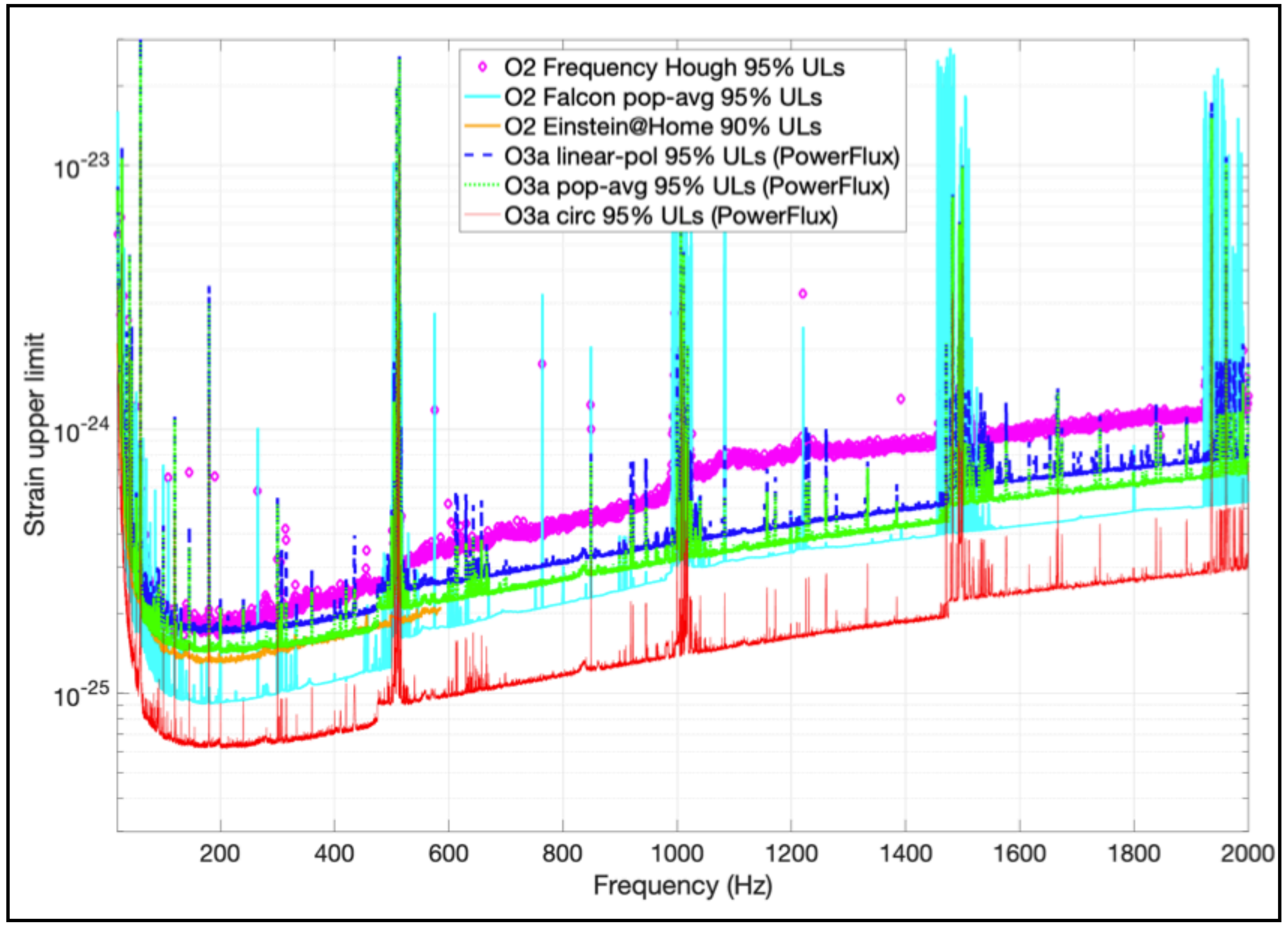
Consistent with BH masses predicted by population synthesis models for NSBHs

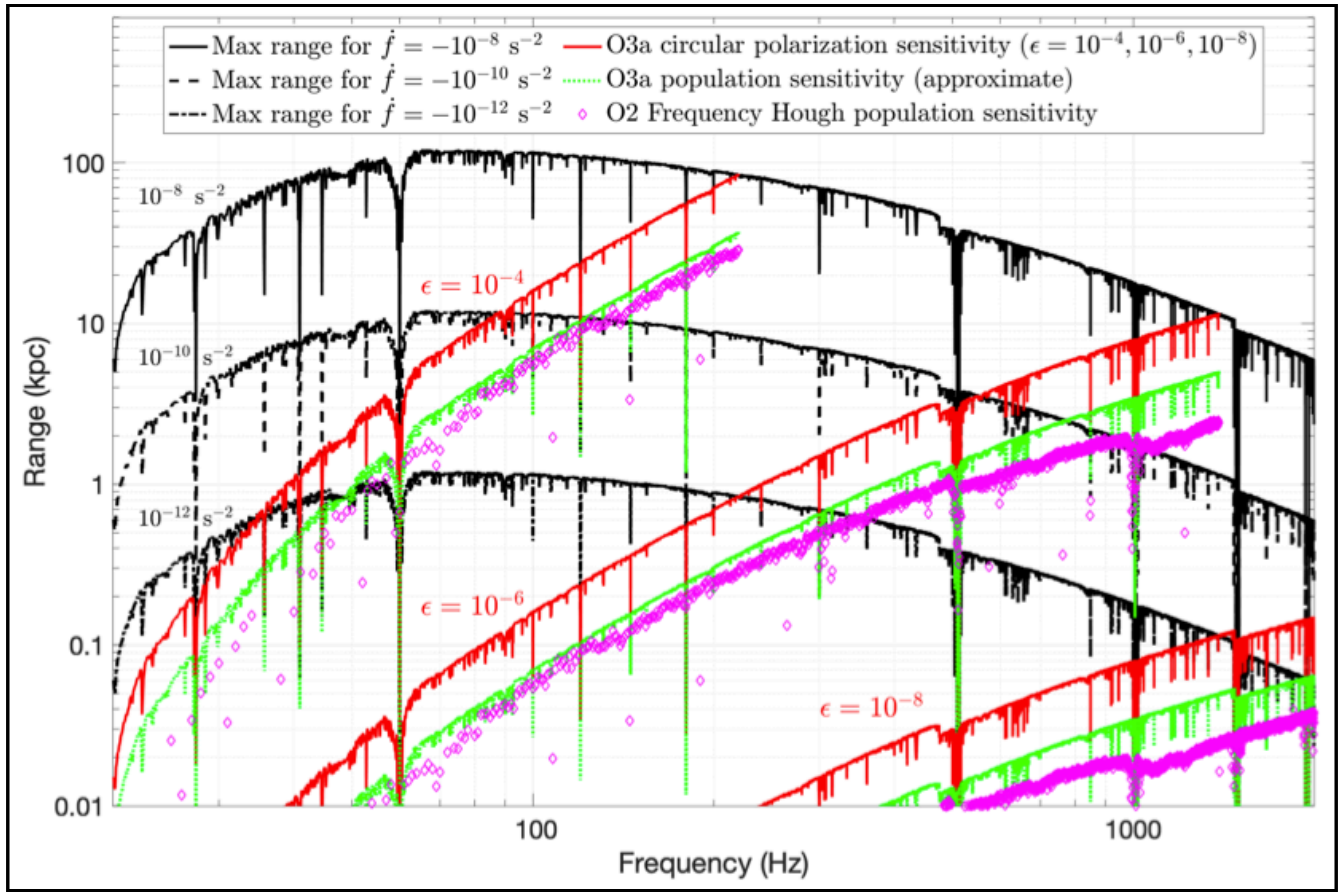
Consistent with observed NS mass distribution in the Milky Way

SEARCH EFFORTS FOR OTHER TYPES

CONTINUOUS GWS FROM ISOLATED NEUTRON STARS

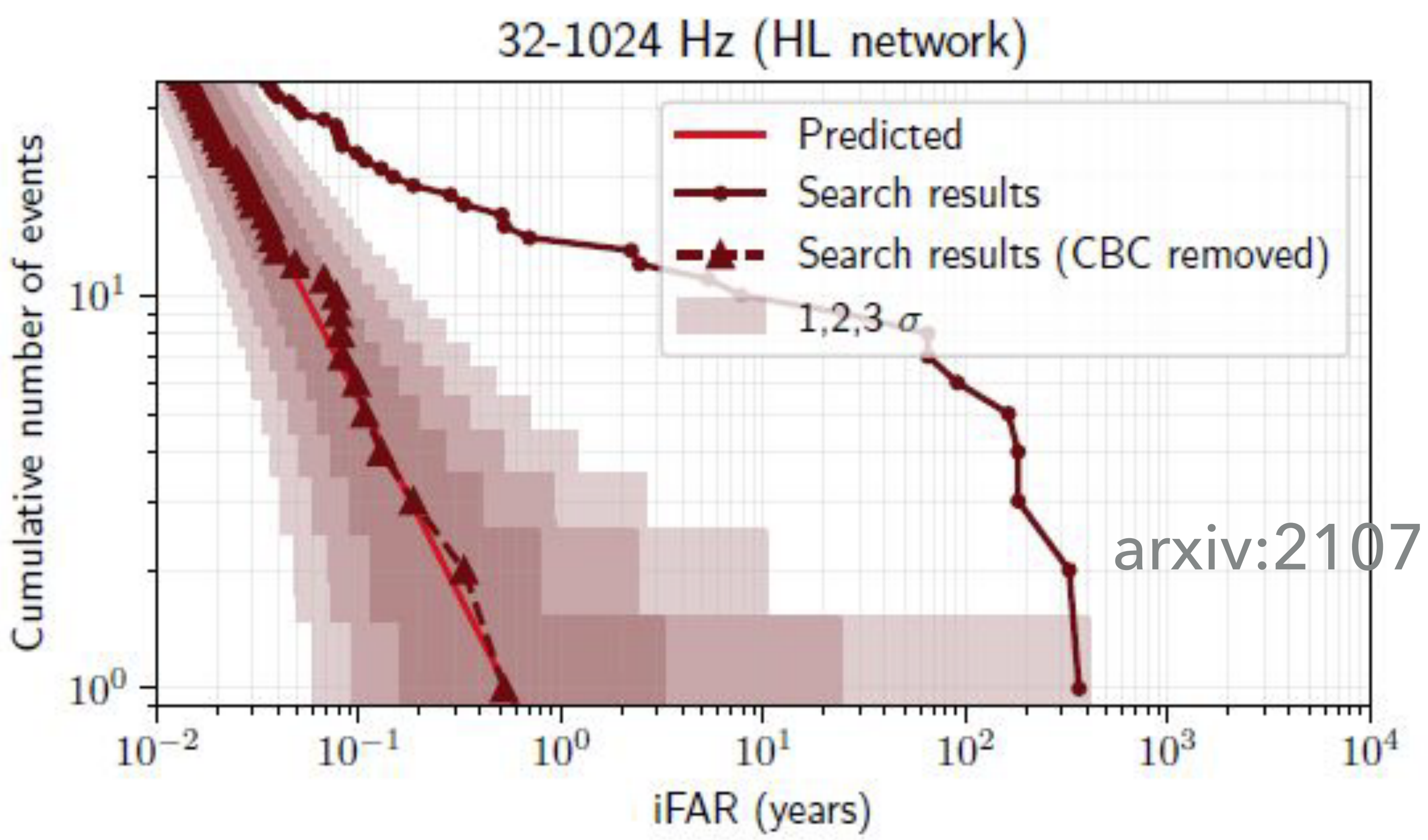
- Continuous GWs could be produced by a nearby, spinning and slightly non-axisymmetric isolated neutron star in our galaxy.
- All-sky search for continuous GWs in the first six months of O3: arxiv:2107.00600 (paper has been accepted by PRD)
- Freq band $[20 : 20\,\mathrm{k}]$ Hz
- Most sensitive search for unknown non-axisymmetric neutron stars with high allowed spin-down magnitudes (up to 10^{-8} Hz/s)
- No detections, upper limits estimations



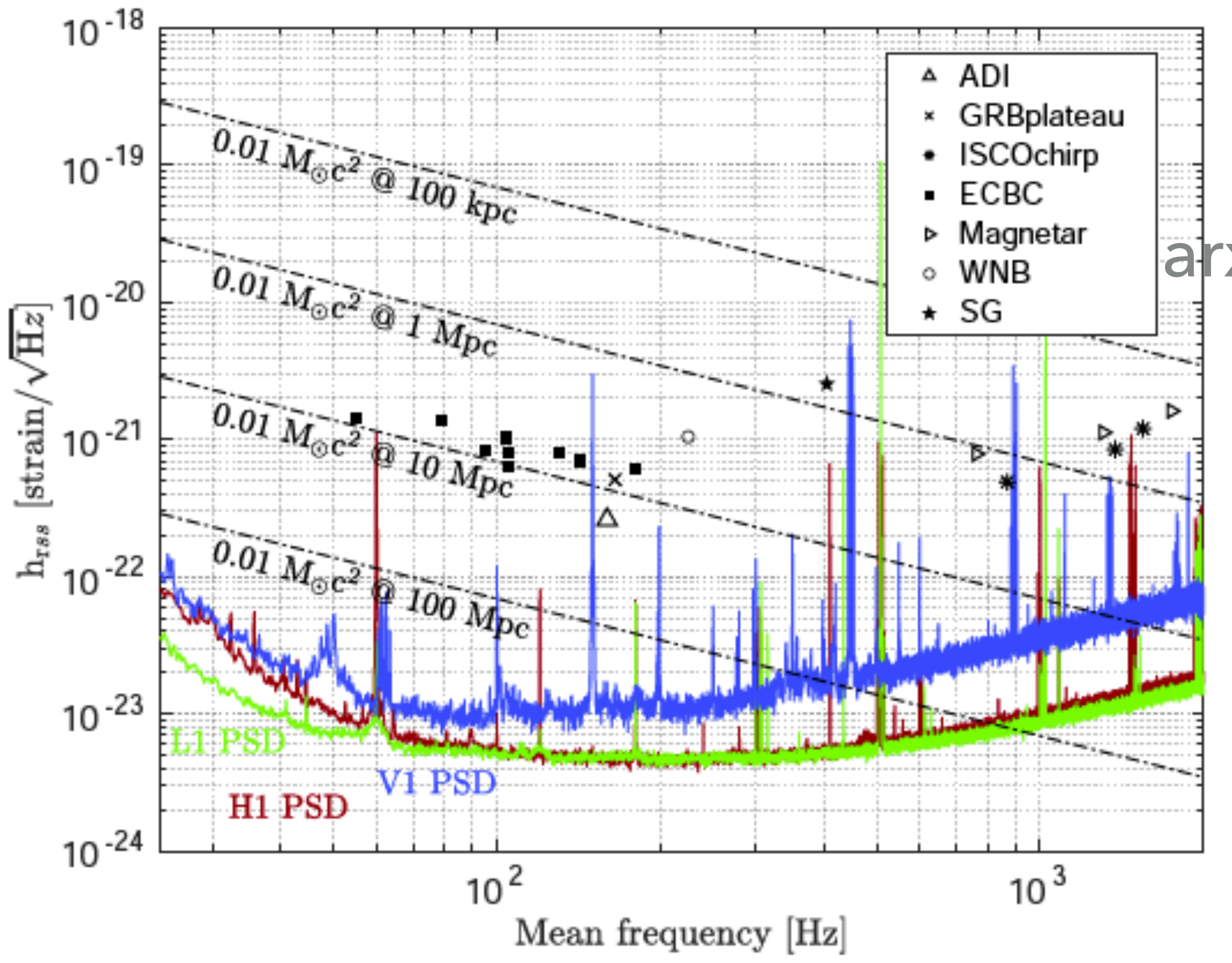


TRANSIENT UN-MODELLED SEARCHES

- All-sky search for short GWs bursts. Sources: BBH, **CCSNe**, **cosmic strings**, pulsar glitches.
    - O(ms) - O(second)
    - No new candidates
    - Set current upper limit
- All-sky search for long GWs bursts. Sources: fallback accretion, accretion disk instabilities, newborn neutron stars from BNS merger or CCSNe, eccentric compact binary coalescences.
    - 2-500 s
    - No new candidate
    - Sensitivity study



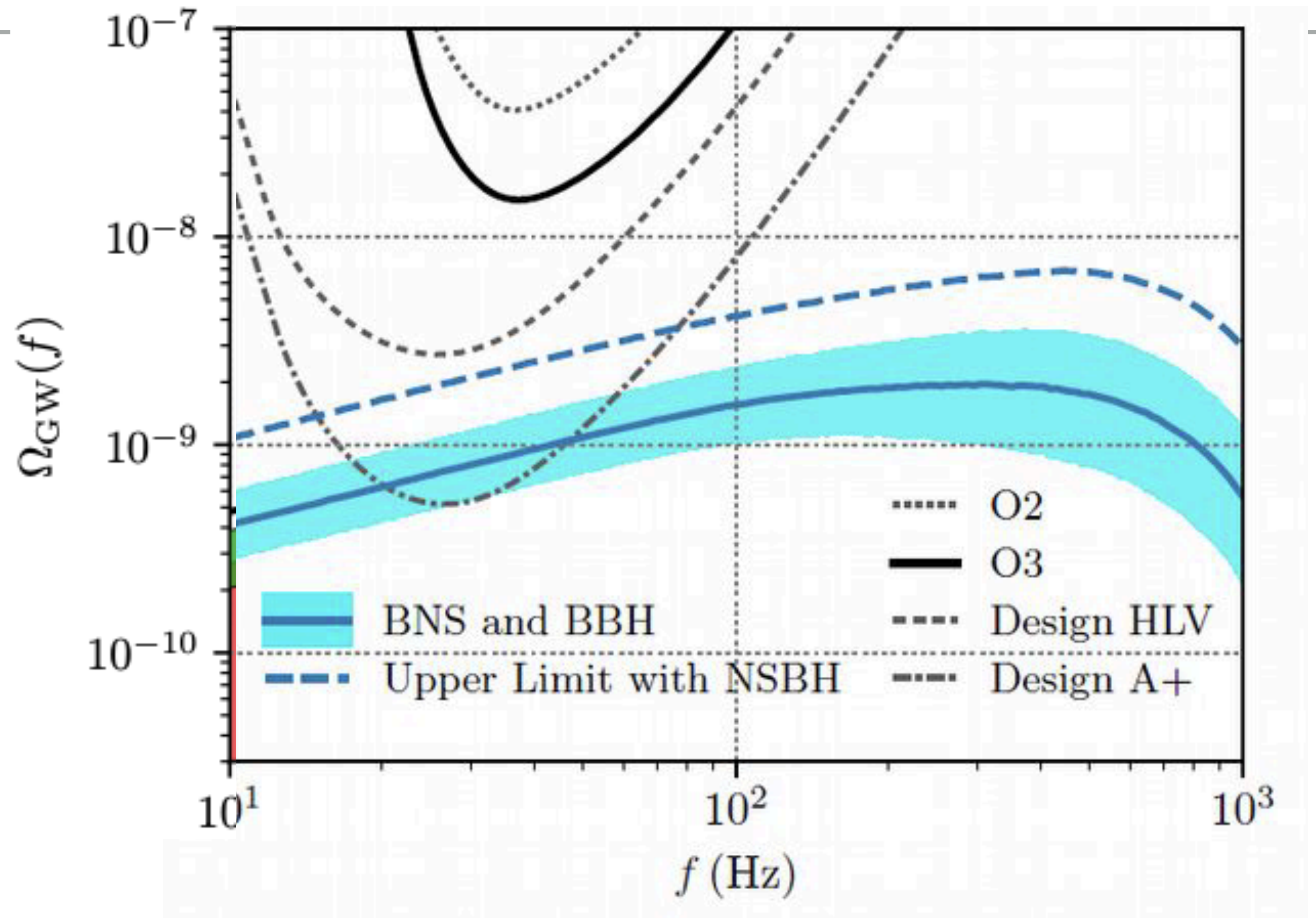
arxiv:2107.03701

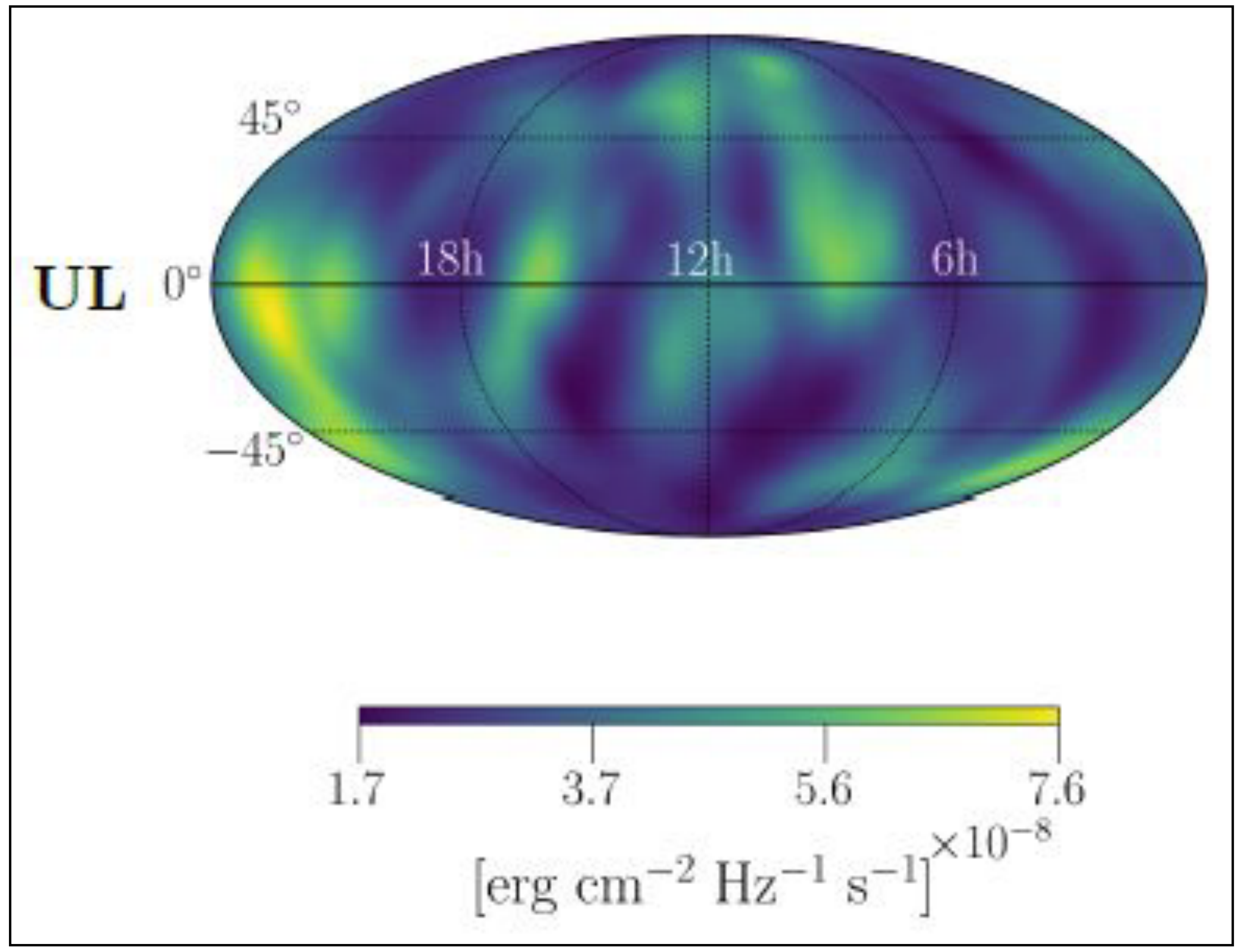


arxiv:2107.13796

SEARCH FOR GW BACKGROUND

- Search for isotropic GW background (astrophysical and cosmological): Phys. Rev. D 104, 022004 (2021)
  - O3 data
  - no significant evidence for a GW background
  - up to date limits on strength of background (upper limits improved previous bounds by about a factor of 6.0)
- Search for anisotropies stochastic in GW backgrounds: Phys. Rev. D 104, 022005 (2021)
  - No significant evidence for a gravitational-wave background.
  - direction-dependent upper limits set on GW emission, improving upon existing limits by a factor of≥2.0

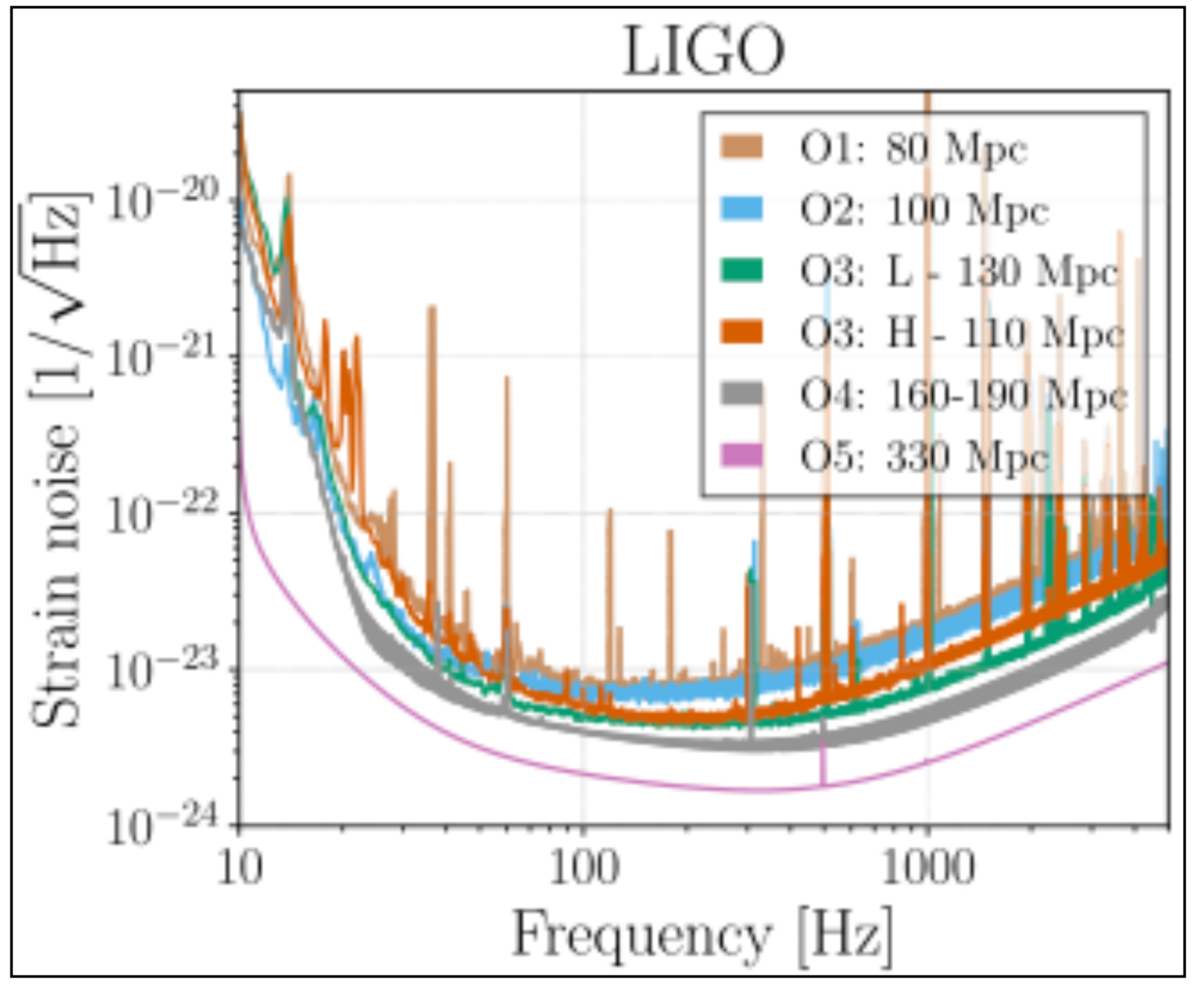


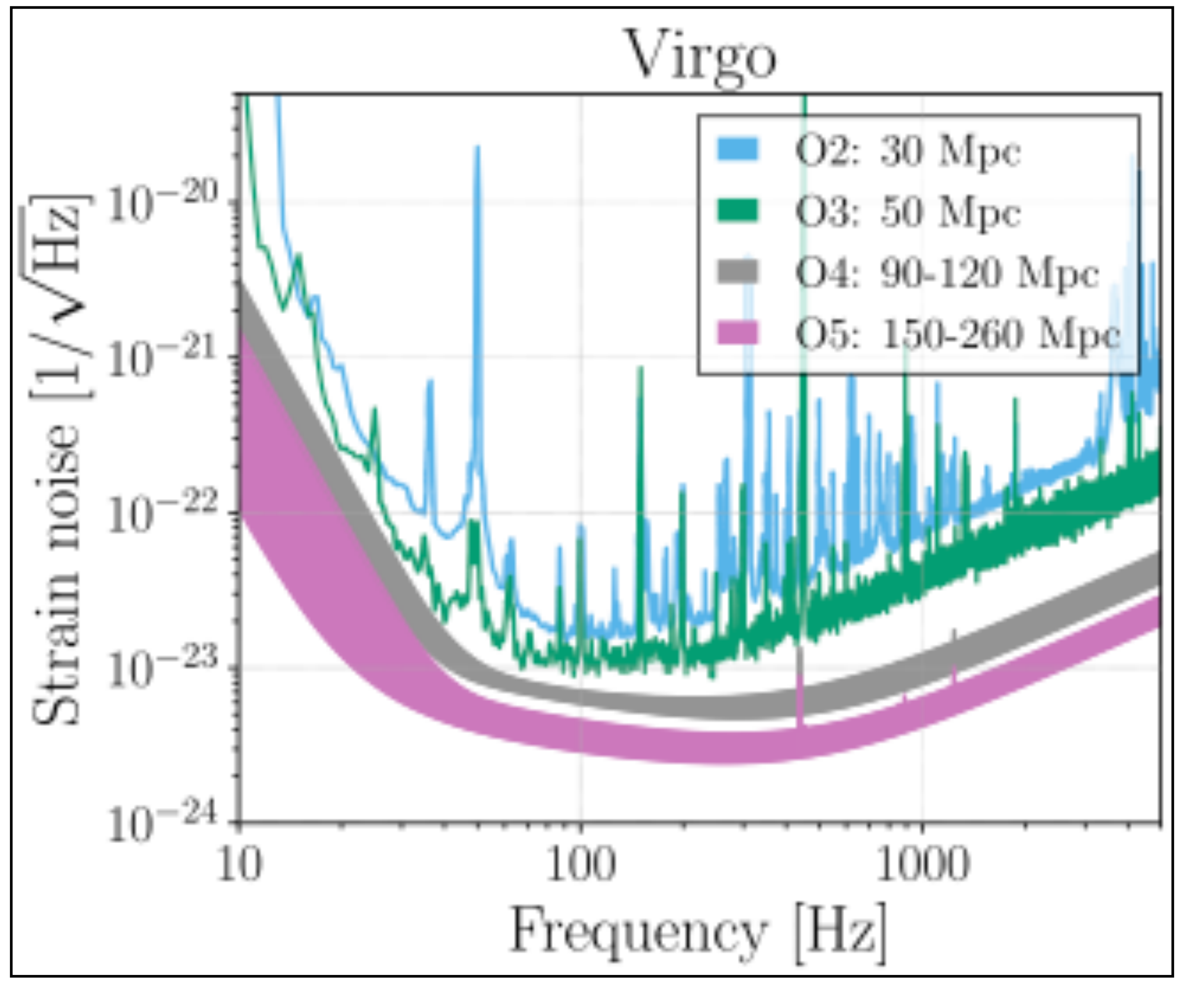


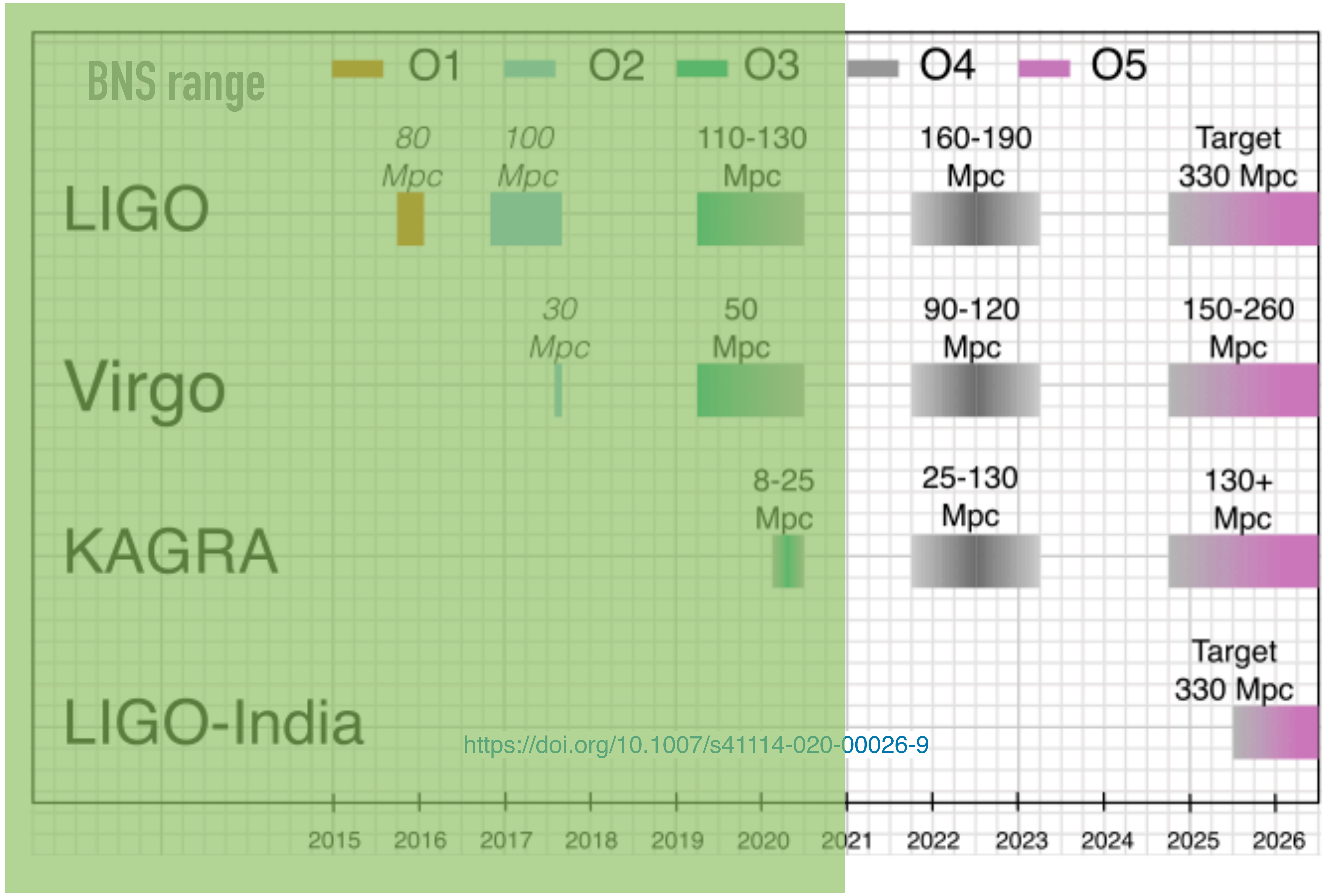
upper limit (UL) sky maps of the gravitational-wave energy flux.

THE FUTURE OF GW ASTRONOMY (AND MULTIMESSENGER)

- O1 rate $\lesssim$ 1 in a month
- O2 rate ~ 1 in a month
- O3 rate $\gtrsim$ 1 in a week
- …
- O5 rate ~ O5Vol/O3Vol * O3rate ~ **few per day**







Abbott et al. 2020. LRR 23:3

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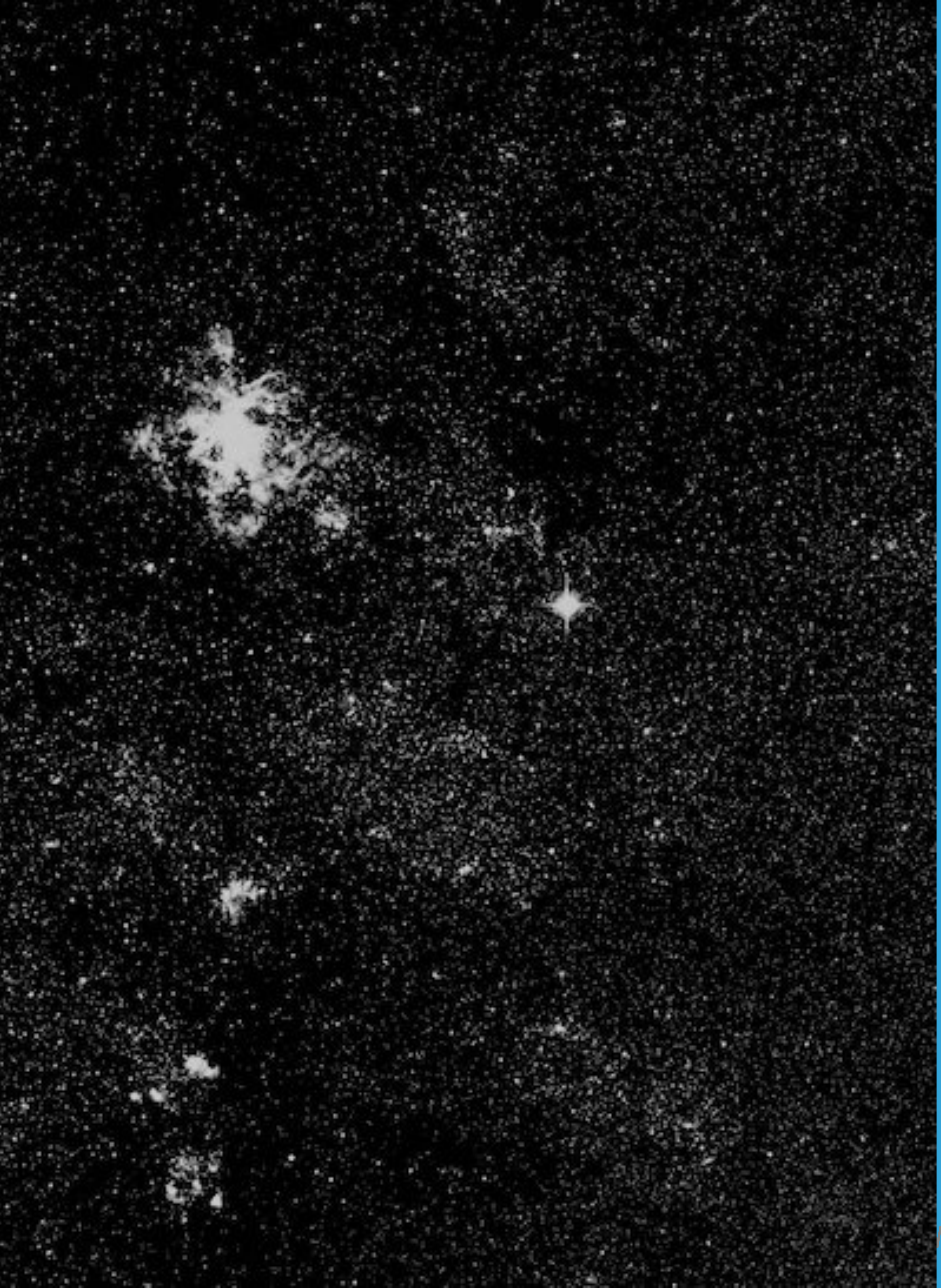

THANK YOU

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